DTIC FILE COPY

(1)

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS NONE
2a. SECURITY CLASSIFICATION AUTHORITY 2b. DECLASSIFIC	3. DISTRIBUTION/AVAILABILITY OF REPORT APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.
4. PERFORMING AD-A222 736	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFIT/CI/CIA- 90-011D
6a. NAME OF PERFORMING ORGANIZATION AFIT STUDENT AT Univ of Illinois/Urbana 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION AFIT/CIA
6c. ADDRESS (City, State, and ZIP Code)	7b. ADDRESS (City, State, and ZIP Code) Wright-Patterson AFB OH 45433-6583
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification) (UNCLASSIFIED)

Cognitive Requirements for Aircraft Navigation

12. PERSONAL AUTHOR(S)
Anthony Joseph Aretz

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
~~THESIS~~/DISSERTATION	FROM ____ TO ____	1990	116

16. SUPPLEMENTARY NOTATION
APPROVED FOR PUBLIC RELEASE IAW AFR 190-1
ERNEST A. HAYGOOD, 1st Lt, USAF
Executive Officer, Civilian Institution Programs

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

DTIC ELECTE JUN 15 1990 S B D

90 06 15 069

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL ERNEST A. HAYGOOD, 1st Lt, USAF	22b. TELEPHONE (Include Area Code) (513) 255-2259 / 22c. OFFICE SYMBOL AFIT/CI

DD Form 1473, JUN 86 Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE

COGNITIVE REQUIREMENTS
FOR AIRCRAFT NAVIGATION

BY

ANTHONY JOSEPH ARETZ

B.S., United States Air Force Academy, 1980
M.A., Wright State University, 1982

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Psychology
in the Graduate College of the
University of Illinois at Urbana-Champaign, 1990

Urbana, Illinois

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

THE GRADUATE COLLEGE

MARCH 1990

WE HEREBY RECOMMEND THAT THE THESIS BY

ANTHONY JOSEPH ARETZ

ENTITLED COGNITIVE REQUIREMENTS FOR AIRCRAFT NAVIGATION

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR

THE DEGREE OF DOCTOR OF PHILOSOPHY

Director of Thesis Research

Head of Department

Committee on Final Examination†

Chairperson

† Required for doctor's degree but not for master's.

O-517

COGNITIVE REQUIREMENTS
FOR AIRCRAFT NAVIGATION

Anthony J. Aretz, Ph.D.
Department of Psychology
University of Illinois at Urbana-Champaign, 1990
C. Wickens, Advisor

This thesis presents a cognitive analysis of a pilot's navigation task, and using this foundation, describes an experiment comparing a new map display, employing the principal of visual momentum, to the two traditional track-up and north-up approaches. The visual momentum display is based on the characterization of the pilot's navigation task as the maintenance of a cognitive link between two reference frames (RFs) -- the ego-centered reference frame (ERF) and the world-centered reference frame (WRF). The ERF corresponds to the pilot's forward view of the world and the WRF corresponds to a north-up geographic map. The new map display employs visual momentum by presenting the ERF, in the form of a perceptual wedge, in the context of a north-up map's WRF. An experiment was conducted to assess the different displays using licensed pilots to perform diverse navigation tasks in the context of computer simulated helicopter missions. As predicted, the data showed the advantage to a track-up map is its congruence with the ERF; however, the development of survey knowledge is hindered by the inconsistency of the rotating display. The stable alignment of a north-up map aids the acquisition of survey knowledge, but there is a cost associated with the mental rotation of the display to a track-up alignment for

tasks involving the ERF. The data also show that the visual momentum design captures the benefits and reduces the costs associated with the two traditional approaches.

Acknowledgements

This thesis was supported by a grant from NASA Ames Research Center, NAG-2-308. I would like to thank Ms. Sandra Hart who served as the technical monitor. I would also like to thank my advisor Dr. Chris Wickens who served as my mentor. Without his expertise, and fast reading of the drafts, my progress on this thesis would have been much more difficult. The U. S. Air Force, especially the Department of Behavioral Sciences and Leadership at the U. S. Air Force Academy and the Air Force Institute of Technology, also deserves gratitude for providing me with the opportunity to conduct this research. Finally, my wife Terry merits the greatest appreciation for her love and encouraging support during those difficult times that all graduate students face. She had the more difficult job of raising our three boys while I studied.

Table of Contents

Introduction

If you ever have the chance to be with a group of pilots and want to get a heated discussion going, tell them the next generation aircraft is going to have an electronic map in the cockpit and ask if they would prefer a track-up (i.e., the top of the map is aligned with the forward motion of the aircraft through the world) or north-up (i.e., north is at the top) alignment. What you will find is that some pilots will testify to the advantages of a track-up alignment (e.g., left and right turns are directly represented on the map), but others will desire the orientation consistency of a north-up map (e.g., providing a stable frame of reference; see Baty, Wempe, and Huff, 1974; Baty, 1976; Hart and Wempe, 1979; Hart and Loomis, 1980; Harwood, 1989). It is not likely that the ensuing debate will arrive at a satisfactory conclusion.

The reason an agreement will be difficult is there may be definite advantages and disadvantages to either alignment. These differences may be the reason previous attempts to establish the relative performance benefits of either alignment have failed (Baty, Wempe, and Huff, 1974; Baty, 1976; Harwood, 1989). There also has been very little research aimed at developing a cognitive model of the navigation task that could be used to provide a theoretical perspective on the issue (Cooper, 1989).

Most of the research that does exist has used relatively simple static tasks in single-task conditions. In contrast,

aircraft navigation is dynamic and must take place in a cockpit's multi-task environment. The pilot's other tasks could potentially compete for the cognitive resources demanded by navigation. These potential task interactions could influence the relative performance of either a track-up or north-up alignment.

In an attempt to provide a theoretical perspective for these issues, this thesis describes a comprehensive cognitive analysis of the pilot's navigation task and identifies important gaps in existing knowledge. Based on this foundation, a cognitive theory is developed for flight navigation. Different approaches to map design are analyzed in the context of this theory and a new design, based on the concept of visual momentum (Woods, 1984), is proposed. An experiment was performed to examine both the theory and its implications for map design. The pilot workload implications of the designs, in terms of cognitive resource demands, were also explored. Human factors design guidelines for electronic navigation displays are also presented.

Navigational awareness

A useful place to start in the analysis of aircraft navigation is to characterize the pilot's task. When a pilot navigates using visual reference points, as opposed to instrument navigation, the desired course is usually represented as a layout of navigational checkpoints on a paper map. Visually salient geographical features and landmarks in

the world serve as these checkpoints so a correspondence between the map and the world is easily maintained. The task of keeping the aircraft on course by matching the geographical features with the map's navigational checkpoints forms the basis of aircraft navigation. "Navigational awareness" is a term that is used in this thesis to describe the cognitive element of this task. In other words, navigational awareness corresponds to a pilot's knowledge of the aircraft's current location and heading relative to the desired course.

Navigational awareness is viewed in the current theoretical framework as the maintenance of a cognitive coupling between two reference frames (RFs) that correspond to the map and the forward view of the world (Aretz, 1989; Harwood, 1989; Wickens, Aretz, and Harwood, 1989). The ego-centered reference frame (ERF) is established by a pilot's forward view out of the cockpit and directly corresponds to the ego-centered perspective view. Verbal references to geographic features in the ERF will consist of clock directions and bearings (e.g., left or right) relative to the pilot. Further, since the pilot and aircraft are bound together during flight, the aircraft's heading will provide the canonical axis by which these ERF directions are judged. For example, the pilot's left will correspond to the region left of the aircraft's current heading. Hence, the physical geometry of the ERF contains the pilot's current location at the origin, with the aircraft's

heading serving as the canonical axis by which all ego-centered referenced directions are based.

In contrast to the relative geometry of the ERF, a world-centered reference frame (WRF) is established by an externally imposed geometry. In aircraft navigation, the WRF is usually defined by the cartesian space of a visually presented map. Since the standard alignment of a map is usually north-up, cardinal directions and compass headings are used to describe locations within the WRF.

In order to navigate, a pilot must be able to represent the current view of the world in terms of it's location in the map. Hence, navigational awareness corresponds to the ability of a pilot to answer the question: Am I (the ERF) where I should be (in the WRF)? To answer this question, a pilot will identify salient landmarks within the map (the WRF) and attempt to locate these landmarks in the forward view (the ERF). If a pilot is successful in relating the ERF to the WRF, then navigational awareness will be achieved. If a pilot is not successful, then navigational awareness will not be achieved and disorientation will result.

Spatial cognition

The conceptual framework presented in this thesis is based on the assumption that a pilot must maintain a cognitive coupling between the ERF and WRF in order to navigate. Four cognitive operations will be required to maintain this coupling

-- triangulation, translation, mental rotation, and image comparison.

The decomposition of navigational awareness into different components was initially derived from data provided by Harwood (1989). In her experiment, licensed pilots flew a simulated helicopter nap-of-the-earth (NOE) mission through a complex world of computer generated objects. The pilots flew a 15-20 minute flight, navigating to different objects designated by visually presented "fly-to" commands. The world was presented on one computer graphics monitor and the map was presented on another. Half the pilots flew with a track-up map and half with a north-up map. In addition to flying the helicopter, the pilots had to perform navigation tasks that varied in the type of information required to integrate the map with the forward view.

The data from Harwood's experiment were complex and revealed no overall advantage to either map design. However, the data did contain a pattern of interactions among navigation tasks, map design, and aircraft heading (generally north vs. generally south) that lead her to propose a two component model of navigation. The first component, orientation, involves the decision "which way do I turn?" and requires a bearing to a specific landmark. The other component, localization, involves the answer to the question "where am I?" and requires the integration of specific landmarks between the map and world.

Harwood (1989) hypothesized that the navigation tasks in her experiment varied in their orientation and localization requirements and were thus sensitive to the alignment of the map display. Tasks with an orientation component were aided by a track-up alignment since there was a direct correlation between the locations in the map and in the world. In contrast, tasks with a localization component were aided by the consistent alignment of a north-up map, allowing for easier search and identification.

Harwood's (1989) navigation model formed a basis for the present treatment and is elaborated into four processing components: triangulation, mental rotation, image comparison, and translation. The _triangulation_ component is related to Harwood's localization process and establishes the geometries of the ERF and WRF. The _mental rotation_ component is related to Harwood's orientation process and is the cognitive operation that aligns the WRF with the ERF. The _image comparison_ component is also related to Harwood's orientation process and confirms that the WRF and ERF do in fact align. _Translation_ is a fourth component not discussed by Harwood and is the process by which pilots monitor their motion through a WRF. A detailed discussion of these four components is presented as follows:

Triangulation. In order for a pilot to determine the aircraft's current location within the WRF, landmarks within the pilot's ERF must be mapped onto checkpoints in the WRF. The information used in the mapping must uniquely specify a

location in the WRF in order for the pilot to be confident in the outcome of this process. Triangulation refers to the technique used in navigation to specify a location on a map (i.e., in the WRF).

Triangulation is a property of geometry that given two points in space, two non-parallel lines drawn from these points will intersect at a unique third point, thereby forming a triangle. In navigation, triangulation may require a minimum of two landmarks and the bearings from those landmarks. Levine, Jankovic, and Palij (1982) refer to this requirement as the two- point theorem of spatial problem solving, but two landmarks aren't always required. Levine et al. (1982) also state that one landmark will suffice if a direction and distance to the landmark are known. For example, a known direction in the world (e.g., by using the setting sun, the bearing of a known road or railroad, or the known heading of an airport runway) can be used to align a map. Once a map is aligned with the world, only the distance to one landmark is required to uniquely specify a location. As a result, either the bearings from two landmarks, or the bearing and distance from one landmark, is sufficient to triangulate a location within a map.

In contrast to this standard definition of triangulation, the current framework refers to triangulation as the perceptual encoding of a unique geometry, i.e., axes and their origin, for each RF. Thus, triangulation must be accomplished twice, once

for each RF. As in the standard approach to triangulation, two pairs of landmarks (i.e., the identical pair in each RF, or one landmark and a known distance) must be used to establish the ERF and WRF. This thesis refers to the traditional use of the word triangulation as localization.

After the ERF and WRF have been specified through triangulation, two cognitive transformations may be required to bring them into congruence (i.e., a one-to-one mapping) -- translation and rotation. As with any two disjoint cartesian coordinate systems, a one-to-one mapping can be established between the RFs by translating the origins and rotating the axes. In aircraft navigation, translation corresponds to the process by which a pilot monitors the aircraft's location (the ERF) as it moves within the WRF. Translation will not be a focus of this thesis.

Even if the origins of the RFs are aligned, the physical rotation of one set of axes into the alignment of the other's axes may still be required before a one-to-one mapping can be established. The current framework suggests that the axes of the ERF and WRF must be aligned before navigational awareness can be achieved. If the orientation of the WRF is not aligned with the orientation of the ERF, one of the RFs will have to be rotated into congruence with the other before the image comparison process can be completed. Further, since the world is three dimensional, three rotations are possible, one for each axis. In navigation only two rotations will usually be

necessary (one in the vertical plane for map alignment and one forward for congruence with the forward view) since a rotation around the line of sight would correspond to a tilted perspective of the world. Consequently, in order to align the axes of the ERF and WRF, the pilot may need to perform two rotations. This thesis examines the hypothesis that these rotations are performed using mental rotation.

Mental rotation. Shepard and Metzler (1971) published the first experiment demonstrating mental rotation. In this study, two three dimensional (3D) images were presented to subjects. The images were either identical or mirror-images of each other and varied in angular disparity by a rigid rotation of 0° to 180°. The task of the subject was to determine if the stimuli were the same or different. The principal finding was that the time required to make this decision increased linearly with the angular disparity between the two images. Several studies have replicated this linear function (e.g., Cooper, 1976; Cooper and Podgorny, 1976; Hochberg and Gellman, 1977; Pylyshyn, 1979). The robustness of this outcome has lead researchers (e.g., Shepard and Cooper, 1982) to propose that the mental rotation of visual images is analogous to the corresponding physical rotation that would occur with the actual object. If this is true, mental rotation may be a fundamental cognitive process.

The hypothesis that a pilot must mentally rotate the WRF into congruence with the ERF before navigational awareness can be obtained rests on this assumption. As previously mentioned,

two mental rotations actually may be required. The first is a vertical mental rotation that brings the WRF into a track-up alignment. This rotation can be accomplished by either physically rotating a paper map or mentally rotating the image of a north-up map. A mental rotation in the vertical plane would not be required if the map were in a track-up orientation to begin with. Second, a forward mental rotation of the track-up image around the horizontal axis and into the forward view must be performed in order for the image to completely align with the ERF.

The extension of mental rotation from visual objects to visual scenes and maps has recently received empirical support from several researchers (Aretz, 1988, 1989; Eley, 1988; Evans and Pezdek, 1980; Harwood, 1989; Hintzman, O'Dell, and Arndt, 1981; Levine, 1982; Shepard and Hurwitz, 1984; Sholl, 1987). The fundamental conclusion from all these experiments is that the mental representation of a paper map is analogous to the physical map itself. Further, if the standard north-up map alignment does not match the direction of travel, then a mental rotation must be performed to bring the map's image (or WRF) into congruence with the forward view (the ERF). The time to accomplish this mental rotation has been found to be proportional to the to the difference between the alignments of the two RF in several navigation related experiments (Aretz, 1988, 1989; Eley, 1988; Hintzman et al., 1981; Shepard and Hurwitz, 1984).

Aretz (1988, 1989) provides data from two experiments that offer evidence for the vertical mental rotation of maps into a track-up alignment. In both experiments subjects were required to compare computer generated symbolic north-up and track-up maps (containing circular colored landmarks) with a computer generated symbolic forward view (consisting of large spherical objects). The main difference between the two experiments was the forward view in the 1989 study contained perspective depth cues. A subject's task was to make same-different judgments between the arrangement of the landmarks in the world and the location specified on the map. The data from both experiments revealed a roughly linear increase in mean response time as a function of the angular difference of the maps from an track-up orientation (i.e., a 0° orientation corresponded to a track-up map). The linear functions were typical of those found in other mental rotation experiments. Further, by varying the presentation sequence of the map and forward view, Aretz (1989) concluded that it was the map that is rotated into congruence with the forward view, and not the reverse. Hence, both experiments (Aretz, 1988, 1989) provide data demonstrating mental rotation in map related tasks.

Shepard and Hurwitz (1984) found that mental rotation also may be required in using a map to determine the direction of upcoming turns. In their experiment, subjects had to decide if the next turn indicated on a map was either left or right; however, the map was not always aligned in a track-up

orientation. The data showed that response times increased linearly with the difference between the orientation of the map and a track-up alignment. Shepard and Hurwitz (1984) concluded that before subjects could make their response, they had to mentally rotate the visually presented map to a track-up alignment.

From the perspective of the framework presented in this thesis, the subjects in Shepard and Hurwitz's (1984) experiment were required to perform a navigation task that required a coupling between an ERF (i.e., left vs. right turn decisions) and a WRF, but they were provided with a map (the WRF) that was not orientated in a track-up, or ERF, fashion. In order to perform the task, subjects had to first mentally rotate the visually presented map into an ego-centered, or track-up alignment. Thus, a navigation task with an ERF component is made easier by a track-up alignment. Data provided by Levine (1982) further support this conclusion by showing that subjects made significantly more errors in using "You are here" maps when the landmarks presented in the tops of the maps did not correspond to what was seen in the forward view. Thus, the preliminary evidence from these four experiments (i.e., Aretz, 1988, 1989; Shepard and Hurwitz, 1984; and Levine, 1982) support the suggestion that maps are mentally rotated into a track-up alignment during the performance of navigation related tasks with an ERF component.

As for the second mental rotation, i.e., forward into the field of view, Shepard and Metzler (1971) demonstrated that mental rotation can occur into the depth plane. Aretz (1988) also provides data for mental rotation into the depth plane in a map related task. In addition to the map-to-world comparisons described above, subjects in this experiment were also required to make map-to-map comparisons. That is, subjects had to compare a north-up map (a WRF) with a track-up map (a rotated WRF). The data possessed an additive increase in the response times for the map-to-world as opposed to the map-to-map comparisons. The increase was roughly of the same magnitude as a 90° mental rotation in the vertical plane. This finding lead to the suggestion that the additive increase was the result of an additional 90° forward mental rotation.

Eley (1988) also provides data supportive of the forward mental rotation component. In this experiment, subjects were asked to compare topographic maps with computer generated worlds that varied in their forward projection angle. The results showed that response times generally increased as the angle between the projected world and the map approached 90°.

The results of the mental rotation experiments described up to the this point suggest a preliminary hypothesis concerning navigational awareness. The time required for a pilot to compare the information presented on a map display to the view out of the cockpit should increase linearly with the angular difference between the orientation of the map and the

direction of travel. This function results from the time required to perform a mental rotation of the map display into a track-up alignment, plus an additive constant for the 90° forward mental rotation.

Although the data generally support this prediction, mental rotation might not always be necessary. Hintzman, O'Dell, and Arndt (1981) found that mental rotation was required to compare information with respect to a visually presented map (i.e., a linear mental rotation function), but not with a cognitive map (i.e., a non-linear and non-monotonic function). Hintzman et al., (1981) proposed that the learning involved in developing a cognitive map of a spatial layout may eliminate any canonical alignment. Any orientation within a cognitive map can be accessed without the need for mental rotation. Thus, as experience in an environment increases, a cognitive map may develop in long term memory that eliminates the need for mental rotation.

Sholl (1987) corroborated this finding using a task that was related more to navigation. In her study, subjects were asked to point to the locations of cities learned either from a map or by direct experience. When the locations were acquired through direct experience, subjects had less difficulty pointing to locations in front than in back, regardless of their orientation with respect to a compass. When the locations were acquired from a map, however, subjects facing north pointed to cities faster than subjects facing south.

Although she did not specifically investigate the role of mental rotation in this experiment, the data do indicate that acquiring a cognitive map through direct experience eliminates any canonical orientation for the mental representation. If the cognitive map is acquired through the study of a physical map, then there appears to be a preferred north-up alignment of the mental representation. Hence, mental rotation may be necessary to use a cognitive map acquired from the study of a physical map, but not with a cognitive map acquired from experience. The performance differences between front and back locations in the experiential based cognitive map indicate that there also may be preferential positions within the ERF.

Aretz (1989) also found that mental rotation may not be used in making sequential comparisons using short term, as opposed to long term memory (i.e., cognitive maps). In addition to a condition where both the map and the world were simultaneously available for the comparison, Aretz also presented subjects with sequential comparisons in which the map or the world was presented first. Subjects could not acquire a cognitive map in the usual sense as a consequence of experience, but information concerning the map was available in short term memory. The data showed strong evidence for mental rotation in the simultaneous condition (i.e., a linear response time function), but not in the sequential condition (i.e., non-linear and roughly monotonic). On the other hand, there was a monotonic increase in the error rate as a function of angular

disparity in the sequential condition. Thus, when a map was visually available during the comparison, mental rotation was performed, and when a map was not visually available, mental rotation was not performed. When mental rotation was not used, however, there was an associated cost in the error rate.

Aretz and Wickens (In Preparation) propose that the non-rotational strategy results from the difficulty of the sequential comparisons. Before a mental rotation can be completed, the image may degrade to a point that it cannot be used as a basis for the comparison decision, thereby forcing the use of a non-rotational strategy. When a map is visually available during the task, it can be used to increase the quality of the image and mental rotation can be performed.

The discussion thus far suggests that mental rotation may play an important role in navigational awareness, particularly when the knowledge is obtained from the study of physical maps. On the other hand, Aretz (1988; 1989) found that mental rotation accounted for only a small proportion of the experimental variance in relation to the other variables or individual differences in these experiments. If mental rotation was not performed, however, a corresponding increase in the error rate can be expected. In terms of a model of navigational awareness, both response time and errors must be considered.

If mental rotation is to be included in a model of navigational awareness, it must be kept in mind that the task

fidelity of the experiments on which this suggestion is based falls quite short of actual navigation. The major shortcoming of this research is that the experimental tasks involved static portrayals of novel and irrelevant environments. In flight navigation, a pilot is interacting with a meaningful environment, rather than passively observing isolated stimulus objects. Of the studies cited, only one came close to a realistic setting. In this experiment, Harwood (1989) found that subjects performed orientation tasks better with a track-up map than with a north-up map. She also found that some aspects of performance with a north-up map were sensitive to heading (i.e., generally north vs. generally south). Unfortunately, due to the nature of Harwood's experimental design, it was not possible to determine if subjects were performing mental rotation during the tasks. It still remains to be demonstrated that pilots mentally rotate maps while navigating.

Image comparison. After the triangulation and mental rotation of the RFs, a comparison process must be performed in order to verify that the two RFs do in fact align. If the positions of landmarks in the two RFs do not match after triangulation and mental rotation are completed, then a cognitive coupling cannot be established and navigational awareness will not be acquired. By default, the location specified by the ERF is always correct (i.e., you cannot be in a different location than what you see). Therefore, if the ERF

and WRF do not match, it is likely that the origin of the WRF selected from the map did not correspond to the actual location seen in the ERF. Thus, a new origin for the WRF must be selected from the map and the process repeated. This cycle will continue until a cognitive coupling between the WRF and ERF can be established. If several attempts at this process fail, it is assumed the person is lost and disorientation will result. Although, the image comparison process is included in this discussion for the sake of delineating a comprehensive model of navigational awareness, it is not systematically examined in the experiment.

Navigational awareness during flight. The discussion thus far has concentrated on navigational awareness as static knowledge of a single location. In reality, navigation is an active process of getting from point A to point B. Further, a pilot must make heading changes to get to new locations. In order to aid the maintenance of navigational awareness during flight, a pilot must plan for the turns that result in heading changes. To prevent disorientation, a pilot must anticipate these course changes in order to predict the contents of the new heading's ERF. In this way, a pilot will know when the desired heading has been obtained. Planning is essential in helping to prevent the loss of navigational awareness.

A desired course change can be computed through the transformation of the required heading in the WRF to control actions in the ERF (left vs. right turns). The decision to

turn left or right only makes sense with respect to the pilot's ERF. For example, a required heading change from 270° to 180° in the WRF must be transformed into a 90° left turn in the ERF. One strategy available to the pilot in making this transformation is to mentally rotate the WRF into congruence with the ERF and determine the proper control action from the conjunction of the two RFs.

Before this mental rotation can take place, however, the geometries of the two RFs need to be established. Since a change in heading is usually made at a specified location, the landmark at this location will serve as the origin for each RF. Once triangulated, the two RFs can be mentally rotated into congruence and the desired control action can be computed. If a pilot makes an error in this computation, resulting in an incorrect turn, the pilot may experience disorientation. That is, the ERF that is seen after the turn is completed will not correspond to what was expected. If the attempt to reestablish navigational awareness fails, the pilot will be disorientated.

Consequently, mental rotation also may play an important role in navigation planning. The data supplied by Shepard and Hurwitz (1984) discussed earlier provide evidence for this suggestion. Recall that in the Shepard and Hurwitz experiment, subjects had to determine if the next direction indicated on the map was either a left or right turn. The data show that mental rotation was required to make this decision if the map was not in a track-up alignment. It must be remembered,

however, that subjects in this experiment were not actually navigating through the world represented by the map. Rather, subjects were to imagine that the addition of each new static line segment in the map represented locomotion through a world. The generalization of these findings to dynamic aircraft navigation may be questionable.

Summary. This thesis suggests that in order for navigational awareness to be achieved, a WRF and ERF must be perceptually triangulated and brought into congruence through mental rotation. Once the two RFs are aligned, an image comparison can be made. These cognitive operations are outlined as follows:

1. Triangulate the WRF through the perceptual encoding of the locations and bearings of at least two landmarks in the map, or the bearing of one landmark and it's distance.

2. Triangulate the ERF through a visual search of the forward view for the same landmarks.

3. Mentally rotate the WRF's image into a track-up alignment, if required (i.e., if the map is not in a track-up alignment).

4. Mentally rotate the WRF's image forward through a fixed 90° angle.

5. Mentally compare the WRF and ERF and determine if a one-to-one mapping can be established. If a one-to-one mapping between the two RFs can be established, then navigational awareness is obtained. If a one-to-one mapping cannot be

established, steps one through four can be repeated. If after several attempts a one-to-one mapping is still not obtained, then disorientation will result.

NOTE: The sequence of steps 1 and 2 above can be reversed if the ERF is used in step one rather than the WRF. It may be that a pilot will always encode the WRF first since the landmarks seen on a map will typically be seen in the world, but landmarks seen in the world may not always be represented on a map.

Map display design

Given the theoretical framework just presented, an obvious consideration in the design of an electronic map display is the need to support an efficient cognitive coupling between a pilot's ERF and map's WRF. One central issue is whether a north-up or track-up alignment provides a more effective display of information. Another question concerns possible improvements in either of these traditional approaches. Then again, what should the criteria be for evaluating the different map designs? The theoretical foundation outlined above provides a framework that can be used to examine the various designs in the context of their cognitive implications.

North-up vs. track-up. Of the cognitive processes that support navigational awareness, only the need for a mental rotation of the map into a track-up alignment can be eliminated in the traditional design of a top-down (or God's eye view) map display. If a map display is designed with a track-up

alignment, or if a paper map can be physically rotated, a mental rotation of the map to a track-up orientation would not be required since the major axes of the ERF and WRF are already aligned. The pilot only needs to perform the remaining forward mental rotation into the field of view. Once this is accomplished, the pilot can attempt to establish a one-to-one mapping between the RFs through an image comparison of the landmarks. A track-up design also simplifies navigation planning since all turns are simply left or right of the aircraft's current heading, represented by the middle of the display. Hence, the main advantage of a track-up map is the elimination of a mental rotation of the display to an alignment congruent with the heading of the aircraft.

Based on this reasoning, it would seem that a track-up alignment would be an obvious choice in the design an electronic map. The data do not support such an apparently direct conclusion. Research investigating the relative performance advantages of track-up and north-up maps has failed to find clear evidence to support either design (Baty, Wempe, and Huff, 1974; Baty, 1976; Harwood, 1989; see Wickens, 1984 for a review). One possible reason for these inconclusive findings is that there may be navigation tasks that are better served by the consistent and more stable alignment of a north-up map. For example, a task involving the location of a specific landmark would be better served if the landmark were always in a consistent location on the map (Harwood, 1989). In

a track-up map, the locations of landmarks are not consistent since the map rotates to maintain the track-up alignment. Hence, the identification of specific landmarks in a rotating map may be more difficult.

Other examples of tasks that would benefit from a north-up alignment would be pilot communication with a navigator, another aircraft, or an air traffic controller. In these situations, the orientations of the pilot's ERF and that of the other person may not be congruent. Effective communication would be better served by a common north-up WRF. In general, any navigation task requiring information that goes beyond the pilot's immediate ERF, where the fixed geometry of the WRF dominates, the task will probably be better served by the consistent alignment of a north-up map.

Since some navigation tasks may be better served by a north-up alignment, and still others that may be better served by a track-up alignment, it is difficult to settle on an optimal map design. Tasks that rely heavily on a WRF would benefit from a north-up map, and those that rely heavily on the ERF would benefit from a track-up map. There are currently no data that aid in the development of a taxonomy that would place navigation tasks on a WRF-ERF continuum. Such data would provide the basis for design decisions concerning map alignment. For example, if the continuum was found to be heavily weighted on the WRF end, a north-up map would be the best design choice. On the other hand, a heavy ERF weighting

would support a track-up alignment. An equal WRF-ERF distribution would support the justification for both, i.e., the possibility of a pilot selectable alignment.

Visual momentum. One problem with a flexible or pilot selectable map alignment would be the inconsistent display presentations. Under stress, a pilot may forget that the map is in a north-up alignment and turn towards a checkpoint that is not there. A possible alternative to a flexible alignment may be to settle on the one alignment that is in general more efficient and use the principal of visual momentum (Woods, 1984) to facilitate tasks that benefit from the other alignment.

The principle of visual momentum states that when an operator must integrate information across successive views of displays, it is best to provide information concerning the relation of one view to another. Visual momentum aids the operator in maintaining a cognitive representation of the process being represented by presenting one display's information in the context of the other. The goal is to provide perceptual landmarks, or anchors, that aid in the maintenance of a cognitive representation of the data. For example, a command status display can provide visual momentum by presenting information in an arrangement that corresponds to the physical relationships among the lower level displays.

Since a pilot must integrate information between an ERF and WRF during navigation, it might be productive to provide

visual momentum concerning the relation of one RF to the other. Harwood (1989) attempted to provide visual momentum in her navigation display by including symbolic color codes that linked the map with the world, but the performance data did not reveal any consistent advantages for this design. The current thesis proposes that instead of using symbolic information, visual momentum can be made more effective by portraying the forward view (the ERF) in the map display (the WRF).

The implementation used in this thesis consisted of two lines forming a wedge emanating from the aircraft symbol. This wedge encompassed an area of the map that corresponded to the pilot's forward field of view. One line was blue and one was yellow, representing the left and right edges of the forward view, respectively. (Blue and yellow were chosen because these are the traditional colors used to represent left and right in a cockpit VOR display.) A third black line bisected this wedge and corresponded to the aircraft's heading. The purpose of this third line was to reduce the mental extrapolation of the aircraft's heading that must be made to distinguish right from left in the ERF. It has been shown that linear extrapolation requires spatial processing resources (Goettl, 1985). Together, these three lines depict the pilot's ERF. Visual momentum between the two RFs was provided by presenting ERF wedge in the context of a north-up map (the WRF).

The reason a north-up map was selected for this design relates to the advantage of a consistent alignment as described

earlier. Beyond this, the visual momentum provided by the ERF perceptual wedge offers several advantages. First, the wedge provides a direct indication of the pilot's ERF in the display. Second, the heading line provides a direct cue for the specific amount of mental rotation needed to bring the ERF and WRF into congruence. Without this cue, the amount of mental rotation required may be ambiguous and lead to inconsistent performance. Third, the heading indicator directly bisects the WRF into the left and right sides associated with the ERF. Fourth, the perceptual wedge aids triangulation by providing a direct indication of the ERF-WRF coupling. Thus, the ERF perceptual wedge should aid performance in any task requiring the cognitive mapping between a WRF and ERF. By providing visual momentum in a north-up map, it is hoped that a good compromise has been reached between traditional track-up and north-up designs.

Cognitive resource requirements

The previous discussion gives an appreciation for the complexities involved in maintaining navigational awareness. In fact, navigation is such a demanding activity that in many military aircraft there is a separate crew member dedicated solely to navigation (e.g., the U.S. Air Force F-15E fighter and the U.S. Army Apache helicopter). In civilian aircraft, navigation is usually the responsibility of the copilot. Still, there are many other single seat aircraft where navigation is the responsibility of the sole pilot. When a

pilot must fly and navigate at the same time, the mental workload imposed by each task may compete for the pilot's limited processing resources and performance could easily suffer in either task.

Given that navigation is such a critical and resource demanding activity, it would be desireable to predict the impact of a pilot's cognitive resource limitations on navigation performance. Unfortunately, there is currently little data that address the cognitive resource requirements of navigation. Nevertheless, using the data that do exist, three preliminary predictions can be made: 1) the maintenance of navigational awareness, including mental rotation, demands spatial processing resources; 2) different navigation tasks may demand varying levels of spatial processing resources; and 3) spatial processing in general, and mental rotation in particular, may be overly sensitive to resource competition and encourage the use of alternative non-spatial strategies.

Multiple resource theory. Multiple resource theory was developed to account for the evidence that two tasks may or may not interact in a way predicted by a single capacity model of attention (Navon and Gopher, 1979; Wickens, 1980, 1984). Wickens (1980; 1984) has proposed a multiple resource model of attention that contains three dimensions, each with it's own dichotomy of limited processing capacity: stage of processing (perceptual-cognitive vs. response), processing code (verbal

vs. spatial), and modality (auditory and visual input vs. vocal and manual output).

The important point for the present discussion is the possibility that spatial processing requires cognitive resources that are distinct from verbal processing. The separation between spatial and verbal processing is very important for aircraft cockpit design because it implies that a pilot's tasks can demand qualitatively different types of attentional resources. An effective cockpit design should strive to reduce competition among tasks for these limited resources in order to promote the highest level of pilot performance.

It was previously suggested that navigation awareness requires a pilot to maintain a cognitive coupling between an ERF and WRF. Since the WRF is a metric space, spatial relationships among landmarks may be important and the required cognitive processing may demand spatial resources. If this is true, then navigational awareness will compete with other spatial tasks for the limited spatial processing resources that are available. On the other hand, if navigational awareness does not demand spatial processing, multiple resource theory predicts that there will be less competition with other spatial tasks.

This thesis examines the hypothesis that there will be competition between flight control and navigational awareness for the limited spatial processing resources. There is

abundant evidence indicating that manual tracking requires spatial resources (e.g., Wickens, Kramer, Vanesse, and Donchin, 1983; Wickens and Liu, 1988; Wickens, Sandry, and Vidulich, 1983). Derrick, McCloy, Marshak, Seiler, and Reddick (1986) provide further evidence that the cognitive processing required to compute attitude changes needed to bring an aircraft to straight and level flight also consume spatial resources. Since flying an aircraft is a combination of manual tracking and attitude maintenance, the cognitive operations required for flying an aircraft primarily demand spatial resources. It has yet to be established that navigation demands spatial resources. If flight control and navigation both demand spatial resources, then performance should deteriorate in at least one of the tasks as competition for the limited resources increases.

Navigation task demands. It is also possible that different navigation tasks could demand varying amounts of spatial resources as a function of the task's reliance on an ERF or WRF. For example, since the ERF is defined in relation to the pilot, locations within the ERF are relative to the body and tend to be labeled using categorical spatial relations that may use verbal, rather than spatial processing. To the right, to the left, in front of, behind, above, and below are verbal labels associated with categorical ERF locations. Kosslyn (1987) has hypothesized that such categorical relations are obtained from left hemisphere verbal processing, rather than

right hemisphere spatial processing (see also Friedman and Polson, 1981). Consequently, an ERF task that uses categorical left-right judgments may demand verbal resources and not compete for the spatial resources demanded by flight control.

This suggestion is supported by a series of four experiments reported by Wetherell (1979). The purpose of these experiments was to investigate short term memory performance in the storage and retrieval of automobile related navigation information. The experiments investigated short term memory effects under actual driving and laboratory conditions using both single and dual task paradigms. The single task conditions required the recall and use of both verbal (i.e., linear written left or right turn sequences) and spatial (i.e., a visual map) navigation information while navigating as a passenger or while performing the laboratory task by itself. The dual task conditions were similar except that the subject was either driving the car or performing a concurrent verbal or spatial task in addition to the navigation task.

The main conclusion from all four experiments was that performance decrements were greatest when more than one task competed for the use of spatial short term memory. Performance was best when the navigation task used verbal lists. This finding was quite surprising given that post-trial memory tests showed that subjects could just as effectively recall either the verbal or spatial information. Hence, navigation performance deteriorated as a result of the use of the

information, not its storage. Wetherell concluded that it was the spatial nature of the maps that caused the performance decrements. It seemed that any additional task requiring spatial memory competed with the use of the stored map to navigate, and navigation performance deteriorated.

Wetherell's hypothesis was that driving and navigating with a spatial map competed for the use of spatial memory and drivers opted to maintain control of the automobile at the expense of getting lost. When verbal lists were used there was little competition and the drivers never got lost. Another interpretation of these results may be that instead of competing for spatial memory as a cognitive structure, driving and navigating also competed for the spatial resources needed to process the information contained in spatial memory. This competition would be based on the need for a continuous mental rotation of the spatial map into congruence with the ERF, i.e., a track-up alignment, before a turn could be made. There was no competition with the verbal lists since they were already compatible with the ERF and no transformations had to be made.

Corballis (1986) describes the only experiment to investigate mental rotation under single and dual task conditions. The results of this study showed that attentional resources were needed to prepare for mental rotation, but not for its performance. Subjects in this experiment were required to mentally rotate letters during the retention interval of either a list of eight digits or the pattern of eight dots.

The data showed that the secondary tasks increased the intercept of the mental rotation function from single task conditions, but not the slope. The largest increase resulted from the concurrent digit memory task. Since these data show that mental rotation seems to require attentional resources for its preparation, the competition between driving and navigating with the spatial map in Wetherell's research could be the result of the need for a continual transformation of the map into a track-up alignment.

Differential sensitivity. If navigation demands spatial resources, another factor to be considered is the possibility that spatial processing may be overly sensitive to resource competition. Any competition among tasks for spatial resources may force a pilot to use an alternative verbal strategy. Wetherell's experiments indicate that the nature of spatial processing is such that only one spatial task can be performed at a time without interference. Verbal tasks may be less susceptible to competition because they have a response-based rehearsal system that can be used to preserve task performance during resource competition. Spatial processing, on the other hand, may rely on a single non-rehearsable visiospatial "scratch pad" (Baddeley and Leiberman, 1980; Logie, 1986). If this is true, then a task that demands this single visiospatial structure may be more susceptible to interference. Several experiments have demonstrated differential dual task decrements for verbal and spatial tasks.

Wickens, Stokes, Barnett, and Hyman (1988) discuss an experiment in which systematic manipulations of stress reduced pilot performance and confidence in aviation related decision making tasks. Increases in background noise, concurrent task loading, time pressure, and financial risk all reduced pilot decision making performance. These effects were strongest for decisions coded as high in spatial demands. For example, a decision coded high in spatial demands required a pilot to integrate information concerning weather conditions, locating advised traffic, and IFR course and speed corrections. In contrast, a decision coded high in memory demands required a pilot to integrate information concerning radio frequency changes required at an IFR intersection. The results showed that increased levels of stress were more likely to disrupt pilot performance in spatial decisions than memory decisions.

Goettl (1985) also provides data that indicates spatial task performance is more easily disrupted by a concurrent task. In this experiment, subjects performed both verbal and spatial memory retention tasks concurrently with verbal and spatial cognitive tasks. Subjects were required to remember either four consonants or four arrow positions while they performed either complex arithmetic or line extrapolation. The results of the experiment showed that performance on the memory task was more easily disrupted by the same type of concurrent task, i.e., there was more interference between two verbal tasks than a verbal and spatial task. The results also indicated that

spatial performance was more fragile since spatial dual task decrements were greater than verbal dual task decrements.

These two experiments (i.e., Wickens et al., 1988; Goettl, 1985), in conjunction with Wetherell's (1979) study, provide support for the hypothesis that spatial performance is more susceptible to resource competition. This sensitivity is probably due to the non-rehearsable visiospatial memory structure needed for spatial processing. Since the metric character of spatial tasks limits the availability of alternative processing strategies, any competition among tasks for this structure will provide for performance decrements. Consequently, spatially based navigation performance may suffer if it competes with other tasks for this structure.

Alternative strategies. The sensitivity of spatial tasks to resource competition is very relevant to aircraft navigation. If flight control and navigation cannot simultaneously use spatial memory, then the data suggest that navigation performance may suffer. This is not desirable in aviation. A pilot must maintain both aircraft control and navigational awareness. Loosing control of the aircraft or getting lost can ruin a mission, or for that matter, destroy the pilot and the aircraft. Consequently, a pilot may be forced to reduce spatial processing competition by using a verbal strategy for the navigation task. For example, a pilot could encode the location of navigational checkpoints using ERF categorical relations, e.g., to the left and above another

checkpoint, as opposed to the WRF's metric spatial relations. Anderson (1978) has noted that any analogue (e.g., spatial) task can be performed, although maybe not as effectively, using an analytic (e.g., verbal) strategy. It may be possible that an alternative ERF based verbal strategy can be used for navigation tasks that are normally performed more efficiently with a WRF based spatial strategy.

If a shift from a WRF based strategy to an ERF based strategy is possible, it would only be necessary under conditions of spatial resource competition. Rock and Nijhawan (1989) have demonstrated such a shift in a simple laboratory task. As attention was withdrawn from an object classification task, the RF for perceiving the object shifted from an earth-centered RF (i.e., a WRF) where gravity defined the "up" axis, to an ERF where head tilt defined the upright.

A similar outcome may also be expected in navigation. As spatial resource competition increases, a pilot may be less able to use a WRF based strategy, and will rely on an ERF based strategy instead. The shift from WRF to ERF processing can also be characterized using Thorndike and Hayes-Roth's (1982) hierarchy of navigation skills. In this hierarchy, navigation knowledge varies from landmark knowledge (i.e., the use of salient landmarks), to route knowledge (i.e., connections of salient landmarks), to survey knowledge (i.e., a cognitive map of the area). A shift from WRF to ERF processing could be described in this framework as a shift from the use of survey,

to route and landmark knowledge. Either way, the strategy shift is from a form of processing where metric relations are paramount, to a form of processing where categorical relations based on the person's view of the world are paramount.

Consequently, under conditions of high resource competition, information presented in a WRF aligned north-up map may be used less effectively than information presented in an ERF aligned track-up map. A north-up map may demand spatial processing since spatial relations must be preserved during the mental rotation of the map into a track-up alignment before ERF processing can be performed. For example, triangulation would be difficult to perform using ERF categorical relations unless the map was track-up, i.e., congruent with the forward view. This suggestion would indicate that there may be greater spatial resource competition when a north-up map is used, particularly on more southerly headings when mental rotation must be performed.

Summary. The studies just described provide data on which to make some preliminary predictions concerning the cognitive resource requirements of navigation. First, navigational awareness demands spatial processing resources. Second, different navigation tasks may demand varying levels of spatial resources as a function of their ERF and WRF information requirements. Third, navigation may be overly sensitive to spatial resource competition and encourage the use of alternative verbal strategies. And finally, the use of a

north-up map may increase spatial resource competition as a result of the mental rotation required to bring the map to a track-up alignment, at least in tasks with an ERF component. These hypotheses are preliminary and are based on fragmentary data from relatively simple tasks that are largely unrelated to aircraft navigation. One of the goals of this thesis is to provide data for the extension of these conclusions to aircraft navigation.

Neuropsychological evidence

The model of navigation described in this thesis characterizes navigation as a one-to-one cognitive mapping between a WRF and ERF. It is interesting to note that the neuropsychological literature also contains references to differences between body (i.e., ego) and world centered deficits. In a review of the neuropsychological data applicable to spatial behavior, Chase (1988) concludes that there is good evidence to support the hypothesis that there is an anatomical distinction between neural circuits for analyzing the environment and egocentric space. It also appears that the hippocampus may serve as the point of integration for these two types of information.

O'Keefe and Nadel (1978) have proposed that the hippocampus is the source of cognitive maps of the environment and that this system is distinct from the representation of egocentric space. O'Keefe and Nadel hypothesize that egocentric space is represented by parts of the neural system

other than the hippocampus, and the role of the hippocampus is primarily to represent environmental space. O'Keefe and Nadel refer to the egocentric neural structure as the taxon system and the environmental structure in the hippocampus as the locale system. The evidence O'Keefe and Nadel provide for the two systems is primarily based on rat lesion studies and show that hippocampal lesioned rats exhibit severe impairment in maze behavior, but not in nonspatial cue dependent learning.

Several other authors have discussed the distinction between ego and environmental centered neurological functioning in humans (Benton, 1977; Benton, 1982; Byrne; 1982; Ratcliff, 1982). The main source of data comes from neurological patients that show a dissociation between disorders of body schema and external space. For example, patients exhibiting left-right confusions do not usually show hemineglect of the left side of the environment, and patients with hemineglect do not usually exhibit left-right confusions (Benton, 1982; Ratcliff, 1982). The locations of the injuries leading to these data have lead several authors to propose that body schema disorders are the result of left hemisphere deficits and external spatial disorders are due to right hemisphere deficits. Ratcliff (1982) also proposes that topographical orientation disorders (i.e., failures in route-finding tasks) are probably the result of bilateral deficits since this disorder is mostly observed in patients with lesions in both hemispheres. These results are consistent with Kosslyn's

(1987) distinction between left and right hemisphere spatial processing discussed previously.

In the current context, the idea that the left hemisphere is responsible for body schema, or categorical relations, and the right hemisphere is responsible for external, or environmental, space can easily be extended to encompass the characterization of navigation as possessing two RFs. Simply put, the ERF corresponds to the body schema and its categorical relations, and the WRF corresponds to external space and its metric spatial relations. Further, the left hemisphere may contain the neural representation of the ERF and the right hemisphere (i.e., the hippocampus as described above) may contain the neural representation of the WRF. Navigational awareness might be established by a neural coupling between the two hemispheres. Even if this suggestion is not true, the neuropsychological data is at least consistent with the behavioral data in suggesting a cognitive distinction between a WRF and an ERF.

Summary

This thesis has characterized navigational awareness as the maintenance of a cognitive coupling between an ERF and WRF. The ERF is established by the pilot's ego-centered view of the world, and the aircraft's forward motion provides the canonical axis by which ERF spatial relations are judged. Thus, the geometry of the ERF contains the pilot's current location at the origin with the aircraft's heading as the canonical axis. In contrast, a WRF is established by the cartesian space of a visually presented map with the standard canonical north-up alignment. Navigational awareness corresponds to the ability to answer the question: Am I (ERF) where I should be (WRF)? To answer this question, the pilot must be able to represent the current view of the world (ERF) in terms of its location on the map (WRF).

The previous discussion also presented the hypothesis that a congruence between the ERF and WRF is established through four cognitive operations -- triangulation, translation, mental rotation and image comparison. Triangulation establishes the geometries of the RFs, translation aligns the origins, mental rotation aligns the axes, and image comparison verifies their congruence. Since these operations are spatial by nature, it was hypothesized that spatially based cognitive processing would be required to support navigational awareness. Further, WRF tasks should also require more spatial resources than ERF tasks (e.g., if mental rotation or metric relations are not

required). Navigational performance also may be more readily disrupted by concurrent spatial activities and force the use of alternative verbal strategies.

The importance of display design in supporting an efficient cognitive interface between the ERF and WRF was also delineated. It is possible that track-up and north-up aligned map displays may differentially influence performance in ERF and WRF tasks. It also may be feasible to provide for visual momentum through the design of a new map display that presents an ERF perceptual wedge in the context of a north-up WRF map display.

The purpose of the experiment described below was to examine three fundamental research issues that are derived from the hypotheses just presented. First, the experiment was designed to assess the significance of mental rotation and triangulation during navigation. In order to address the need for mental rotation, two of the navigation tasks required a coupling between an ERF and WRF and used either a track-up or north-up aligned map. Scene content was manipulated in one of these tasks to assess the importance of triangulation. Second, the experiment examined the nature of the attentional resources required by navigation by including three levels of concurrent demands. And third, the experiment investigated the relative effectiveness of a map display in supporting navigation. This evaluation was made across four different navigation tasks that varied in their ERF and WRF information requirements and used a

track-up map, north-up map, and north-up map augmented by an ERF perceptual wedge to create visual momentum.

Method

In order to create a high degree of realism for the navigation tasks, the experiment was performed in the context of a helicopter simulation similar to that employed by Harwood (1989). A Silicon Graphics 3020 IRIS computer graphics system was used to simulate low altitude NOE helicopter missions through worlds consisting of flat terrain and symbolic landmarks (e.g., solid-colored, geometric shapes). The main purpose of the simulation was to create a realistic cognitive simulation of a typical helicopter NOE mission.

The subjects performed the navigation tasks while they flew through the symbolic world created by the simulation. To prevent subjects from adjusting their airspeed as a function of workload, and possibly diluting the experimental effects, each mission was flown using a fixed throttle setting. Further, to prevent the development of an experiential cognitive map of the world, and conceivably eliminating the need for mental rotation (Hintzman et al., 1981; Sholl, 1987), subjects flew through a different arrangement of the landmarks on each mission; however, the flight path through each particular arrangement was the same for each subject.

Navigational tasks

In general, a subject's task was to fly the simulated NOE missions by using a subset of the symbolic landmarks as navigational checkpoints. The objective of each mission was to navigate through the world successfully without getting lost.

Periodically the subject's aircraft was intercepted by an enemy helicopter. The subject was required to chase the enemy helicopter in order to complete the mission. The experimental purpose of these attacks was to disorient the subjects in relation to their location in the map. These chases will be described in more detail shortly.

Within this basic mission scenario, subjects were required to perform navigation tasks that varied in their utilization of either an ERF or WRF. Four tasks were used that required a range of processing demands, which provided data for the examination of the cognitive operations proposed earlier. These tasks ranged from one requiring only an ERF (i.e., a turn to a visible landmark), to two requiring a cognitive coupling between an ERF and WRF (i.e., a turn to an occluded landmark and localization with a map), to one requiring only a WRF (i.e., map reconstruction). Through this systematic manipulation of task RF requirements, an attempt was made to verify the cognitive model of aircraft navigation developed above. Specifically, the ERF task should not require mental rotation; the WRF tasks should be performed more efficiently with a track-up map and require mental rotation with a north-up map; and the WRF task should be facilitated by a north-up map.

The ERF and WRF turns and WRF localization tasks were presented during the missions and occurred at one of four possible aircraft headings, 0°, 60°, 120°, and 180°. The systematic manipulation of course heading was used to determine

if subjects were mentally rotating a north-up map to a track-up alignment during the performance of the tasks. If mental rotation is being used, response time (RT) should show a linear, or at least monotonic, increase from a 0° to 180° heading.

Subjects did not know the desired course ahead of time but were given visual "fly-to" commands on the IRIS monitor during the mission. The general sequence of events for a mission was as follows. A subject began a mission in the air flying towards the first navigational checkpoint. While enroute to this checkpoint, the subject would fly over an invisible "mine" that would trigger a navigation task. The mine would cause the IRIS to beep and present the subject with a question at the bottom of the screen concerning the next checkpoint. These questions were of the form "Direction of turn to the Blue Pyramid?". Subjects were told to answer either left or right based on the direction they would have to turn to get to this checkpoint when they reached the checkpoint towards which they were currently flying. Subjects were told to respond as quickly as possible while maintaining accuracy by using the left or right button of the flight control stick. After their response, subjects were provided information concerning the accuracy of their response and told to continue the flight to the first checkpoint. Upon reaching the first checkpoint, subjects were provided with fly-to instructions to the checkpoint for which they just answered the question. In other

words, if the question had concerned the blue pyramid, subjects were told to fly to the blue pyramid. In this way, subjects were forced to plan their route changes before they had to make them at the next checkpoint. Each mission progressed in this manner until subjects arrived at the final checkpoint. Each mission lasted approximately 10 minutes.

The mines were used for all the navigation tasks occurring during the mission. Two of these tasks were related to the course change questions just described. The only difference between the two tasks was the visibility of the desired checkpoint. Subjects were told before the experiment that a checkpoint may or may not be visible on any given trial, but they did not have any indication of a checkpoint's visibility until a trial occurred.

ERF course changes. The first task, an ERF course change, involved a checkpoint that was visible in the forward field of view. This is an ERF task because all the necessary information to answer the question was present in the forward view of the world, and there was no essential requirement for the subject to use the map. Subjects only had to look at the forward view on the IRIS monitor and indicate as quickly as possible whether a left or right turn was required to fly to the next checkpoint. Furthermore, to decrease any possible ambiguity in the question, subjects were told before the experiment that all the landmarks in the world were unique based on a combination of color and shape coding.

WRF course changes. In the WRF course change, the desired checkpoint was not visible in the forward view. Thus, in contrast to the ERF course change, this task required a cognitive coupling between the ERF and WRF since subjects had to look at the map to answer the question. To respond, subjects located the checkpoint in the map and indicated whether its location (in the WRF) required a left or right turn (in the ERF) at the next checkpoint. This WRF task was derived from the Shepard and Hurwitz (1984) experiment and was expected to show evidence for mental rotation if the map was not in a track-up alignment.

WRF localization. In the localization task, a subject had to compare the map with the world and determine if the aircraft's location in the map was accurately portrayed, i.e., decide whether the their location in the map's WRF was congruent with their ERF's forward view. The task evolved in two phases. First, when the flight path crossed a mine, an enemy helicopter flew across the path of the subject's aircraft. Subjects were told to respond to this threat by chasing the enemy aircraft in a follow-the-leader manner. The main purpose of the enemy chase was to distract the subject's attention from the navigation task, get them off course, and disorientated with respect to the map. To accomplish this objective, the enemy helicopter's path took the subject to a region of the world that was out of view from their previous course. Once in this area, the subject eventually flew over

another mine that triggered the localization task. The enemy paths were variable and could not be predicted from chase to chase.

During the enemy chase, the map was erased from the bottom computer's screen, and once the localization mine was triggered, the map was updated and the simulation was frozen; however, the map was not always updated accurately. When the map was updated inaccurately, the subject's location in the map was shifted 250 ft. forward or backward and 250 ft. to the left or right. These deformations were randomly established prior to the experiment. Subjects were told that the deformations occurred on at least one, but possibly more, of the trials during the mission. In practice, there were six triangulation tasks in each of the 18 missions. Six of the missions contained one deformation and twelve of the missions contained two, although subjects were not told this information. Subjects were told to indicate (i.e., make a yes-no decision using the two switches on the flight control stick) if their location in the map corresponded to their actual location as seen in the forward view. Subjects were provided feedback concerning the accuracy of their response. If the map was in error, it was accurately updated after the response. Immediately after the response, the simulation resumed and subjects were given a visual fly-to command to proceed to the next checkpoint in the mission.

The localization task was derived from Aretz's (1988; 1989) experiments in which subjects had to detect mismatches between either a track-up or north-up map and a symbolic forward view of a world. The distortions in the current experiment were not artificial, but corresponded to incorrect locations in a map. In comparing the map with the forward view, subjects saw landmarks in their correct relative positions to each other, but not to their own aircraft.

In addition, the information contained in the forward view during the localization task varied from simple to complex. Through a manipulation of scene content, the attempt was made to affirm that the bearings from two landmarks are required for localization. Specifically, the localization tasks occurred in areas of the world where the forward view contained either one, two, or several visible landmarks.

Number of tasks. The subjects performed each of the three navigation tasks several times during each mission. There were four ERF course changes, four WRF course changes, and six localization tasks (four or five with matching views and one or two with mismatching views). Each replication of a task within each mission occurred at a different aircraft heading, i.e., 0°, 60°, 120°, and 180°, in order to investigate a possible role for mental rotation. All segments of a mission were at one of these headings. There were a total of 14 navigation tasks within each mission and the task sequence was randomly determined before the experiment under the constraint that a

single task type could not occur more than twice in a row. Figure 1 presents a typical mission segment showing the layout of five navigation tasks.

WRF map drawing task. Subjects were also asked to perform an additional WRF task on the completion of each mission. Subjects were asked to provide, to the best of their ability, a rough sketch of the world in which they just flew. They were provided with a blank sheet of paper and told to indicate, using any symbology they chose, the shape, color, and location of each object they could remember and the direction of north. Thus, this task required the subject to generate a WRF.

The purpose of the map reconstruction task was to assess the contribution of a map display in the development of a cognitive map (i.e., a mental WRF). Although the experiment was designed to prevent the acquisition of a cognitive map by using a different arrangement of landmarks for each mission, some learning was expected to occur and the consistent alignment of a north-up map was hypothesized to benefit performance.

Summary. The four navigation tasks provide a continuum of information processing requirements that can be used to verify the cognitive model of navigation developed above. The ERF course changes required only an ERF since there is no need to look at the map's WRF, and the response (left vs. right) is linked to the ERF. The WRF course changes required both an ERF and WRF since subjects had to look at the map in order to

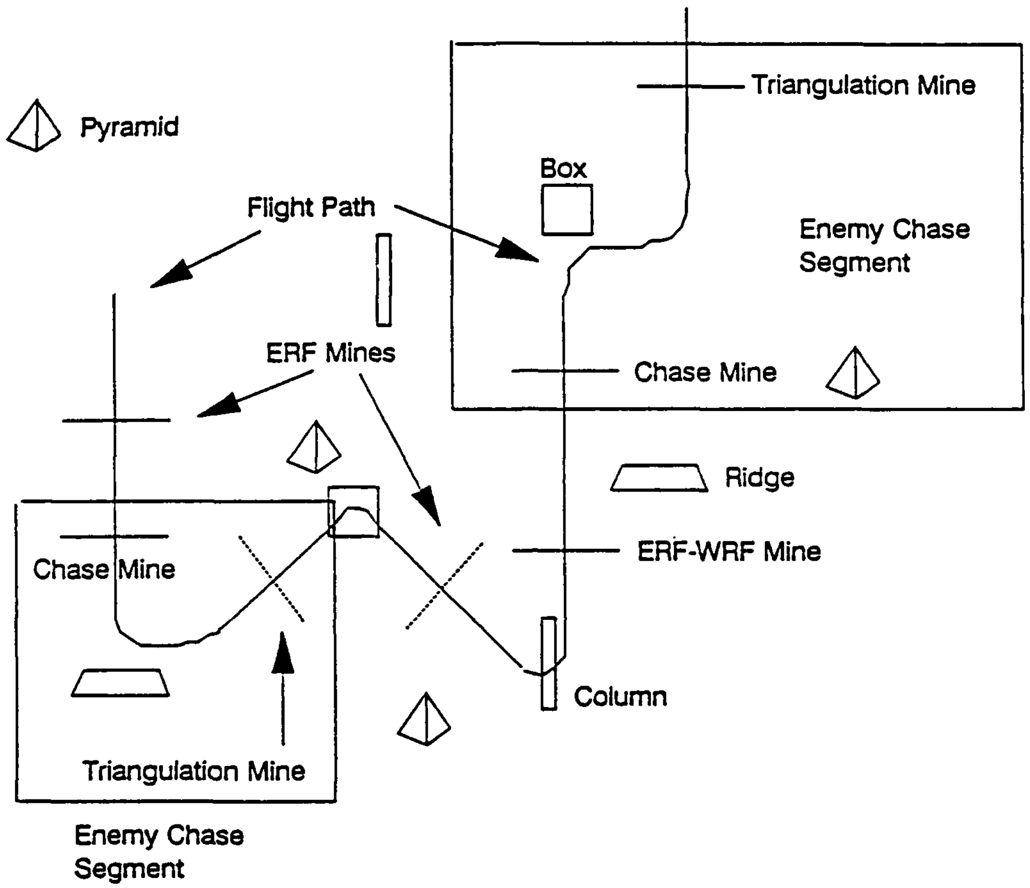

Figure 1. A mission segment showing a typical sequence of five tasks.

locate the landmark in the WRF, and the response was based on their ERF. There was also a possible need for mental rotation in this task if the map was not in a track-up alignment. The WRF localization task required a mapping between the ERF and WRF since there was a need to compare the forward view to the aircraft's location within the map. Again, there was also a possible need for mental rotation in this task if the map was not in a track-up alignment. Finally, the map reconstruction task assessed the ability of a map to support the initial stages in the development of an internal WRF, or cognitive map. To the extent that these four tasks require WRF information, there may be differential effects based on the type of map display.

Workload ratings

Subjects were also required to provide ratings on their perception of the workload experienced during the mission immediately following the map reconstruction task. Subjects were provided with a computer presented version of the NASA TLX subjective workload rating scale. These ratings provided subjective data that was used to compare the workload of the different flights. Research has shown that subjective ratings can dissociate from performance data (Liu and Wickens, 1987; Derrick, 1988; Yeh and Wickens, 1988). At the completion of the experiment, subjects were also asked to fill out a questionnaire concerning the manipulations used in the study.

Map displays

The experiment included three map designs in order to provide human factors guidance for future map displays. To achieve this end, the navigation tasks were aided by: 1) a track-up translating and rotating map; 2) a north-up translating map; and 3) a north-up translating map with an ERF perceptual wedge.

Certain design elements were common to all three displays. The aircraft's current location remained in the center of the display and the map translated beneath as the aircraft flew through the world. The aircraft's current compass heading was numerically presented at the top, center of the display. The amount of the simulated world displayed on the map at any given time was a subset, or window, of the total world. The size of this window included the landmarks that would be encountered in the next few minutes of flight. The symbolic landmarks in the simulated world were presented on the map using colored geometric shapes that were similar to their actual color and shape in the world. There were a total of 28 landmarks, consisting of four shapes (i.e., a pyramid, column, box, and ridge) and seven colors (i.e., white, yellow, purple, red, green, brown, and blue). Shape and color were combined so each landmark was unique and the landmarks were located in different positions for each mission. The differences between the three designs were as follows:

__Track-up map__. The track-up map rotated so that the aircraft's current heading was always towards the top of the display. Thus, the aircraft symbol was fixed in the center of the track-up map while the map translated and rotated beneath.

__North-up map__. The north-up map did not rotate. Instead, the aircraft symbol in the center of the display rotated to provide an indication of the current heading.

__North-up wedge map__. The north-up wedge map was identical to the north-up display, except the ERF information was presented in the form of an ERF perceptual wedge as described earlier. This wedge consisted of three colored lines that emanated from, and rotated with, the aircraft symbol. The lines extended to the edge of the display.

The first two map designs were selected because they are the most common implementations discussed in the human factors literature (see Baty et al., 1974; Baty, 1976; Hart and Wempe, 1979). The wedge design was selected because it provided visual momentum that could capitalize on the advantages found in each of the two traditional approaches. Further, by including all three designs, it was possible to examine their relative effectiveness in the context of the cognitive model outlined previously. By examining a diverse range of map designs and navigation tasks, the most effective approach can be determined.

Task loading

To the degree that the navigation tasks compete with flight control for spatial processing resources, dual task interference can be expected. In order to assess the possibility that the navigation tasks demand different levels of spatial resources and that they may be sensitive to resource competition, three levels of flight control difficulty were employed -- autopilot (no flying requirements), flight control with no control lag, and flight control with a control lag of 350 msec.

The autopilot condition was included because it provides a single task baseline for the navigation tasks. The autopilot was a preprogrammed flight path the computer used to fly the simulation using the same preset speed as in the flight conditions. The autopilot flew roughly the same path as any subject would since the flights were structured so the navigation tasks occurred at specific locations and headings.

The two levels of flight control difficulty provide dual task conditions in which there were progressively more spatial processing demands. Subjects were instructed that flight control was their primary task and they should strive to maintain an altitude of 50 ft. with minimal error. They were also told to perform the navigation tasks as quickly and as accurately as possible while maintaining effective flight control. These instructions were realistic in that flight control must always be maintained to prevent flight

instabilities and a possible crash. All other flight tasks, such as navigation, are secondary to flight control. The sensitivity of the navigation tasks to resource competition can be assessed based on the extent that navigation performance changes as a function of increasing flight control demands.

Psychological testing

Much data exists that indicate there are significant differences among individuals in their ability to perform spatially orientated navigation tasks (Aretz, 1988, 1989; for recent reviews see Evans, 1980 and Thorndyke and Goldin, 1983). Since the navigation tasks in this experiment rely so heavily on spatial processing, standard psychological tests were given to all subjects in an attempt to discover possible covariates for the data analysis. These tests were given to each subject in various sequences on different days of the experiment and included: 1) paper folding and cube comparisons tests (Ekstrom, French, and Harman, 1976); 2) an embedded figures test (Consulting Psychologists Press, 1971); and 3) the chimeric face questionnaire for hemispheric lateralization (Levy, Heller, Banich, and Burton, 1983). Data was also collected from each subject in a shortened version, i.e., 72 trials, of the mental rotation experiment used by Aretz (1989). The data collected from these sources provided a diverse assessment of the subjects' spatial abilities. It was hoped that these data would correlate with a subject's performance in the experiment (e.g., Derrick et al., 1986).

Experimental design

The experiment employed a within-subjects factorial design for all the navigation tasks, but the factors were different for each task. The ERF and WRF turns employed a 2x3x3x4 factorial (i.e., task type x map display x flight difficulty x aircraft heading). The WRF localization task occurred while the simulation was frozen and employed a 3x4 factorial (i.e., map display x aircraft heading). Three levels of scene content (one, two, and three or more) were nested across heading within the localization task. The map reconstruction task occurred at the end of mission and employed a 3x3 factorial (map display x flight difficulty).

Since two of the flight difficulty levels required subjects to control the simulation, the aircraft's heading at the time of task initiation was not always equal to the desired heading. As a result, trials were grouped into the four heading conditions at the completion of the experiment based on the following criteria: headings from 330° to 29° were placed in the 0° group, headings from 30° to 89° were placed in the 60° group, headings from 90° to 149° were placed in the 120° group, and headings from 150° to 209° were placed in the 180° group.

Each subject participated in three experimental sessions on different days. On each day, three practice missions were followed by three data collection missions. The first mission in each block of practice or data collection missions was flown with the autopilot. Each autopilot mission was followed in

sequence by a flight with no control lag and a flight with high control lag. The type of map display used during a mission was blocked across days and the order was counterbalanced to reduce any possible sequential effects. A different world was constructed for each mission, and a specific mission was always used for the same map display and flight control manipulation combination, for a total of 18 missions.

A within-subjects design was selected because of data indicating significant individual differences in spatial abilities (Evans, 1980; Thorndyke and Goldin, 1983). Since the experimental hypotheses rely on spatial processing, it was important to eliminate any possible random contribution of unsystematic variance in the data due to individual differences. A between-subjects design where subjects were assigned to groups based on the spatial assessment battery also seemed to be less precise since any allocation of subjects would not assure an equal distribution of abilities in each group. Thus, the advantages of a within-subjects design outweighed any advantages of a between-subjects design (e.g., negative or asymmetric transfer).

Dependent variables

Mean response time and error scores served as the dependent variables for the navigation tasks occurring during the flight. The number of objects placed in their correct locations served as the dependent variable for the map reconstruction task. RMS scores for both altitude deviation

from 50 ft. and stick velocity (i.e., difference between the current stick position and the previous stick position for each stick input) were computed for the ERF and WRF turn decisions since these were the only tasks during which the subjects maintained flight control. Only the RMS scores for the period during the performance of the tasks were analyzed.

Subjects

A total of eighteen male licensed pilots responded to advertisements on the University of Illinois campus and were paid $4.50 an hour for their participation. The subjects averaged 21.3 years in age and had logged an average of 241 total flight hours (106 of which were cross-country hours). One subject was a rated U.S. Army helicopter pilot, three were certified flight instructors, three were instrument rated, two had their commercial license, one had a multi-engine rating, and the remainder possessed private pilot certificates. The subjects were administered a handedness questionnaire concerning a variety of tasks and all were right hand dominant in all the tasks. The Ishihara (1989) color vision test was also given to each subject and indicated all subjects had perfect color vision.

Results

The data were analyzed in three separate groups based on the experimental design described above. Thus, three within-subject ANOVAs were performed -- one for the ERF and WRF turns, one for the WRF localization task, and one for the map reconstruction task. The data are discussed in terms of these analyses.

The experimental design provided for a total of 2268 possible cases in the flight portion of the experiment (18 subjects x 9 data collection missions x 14 tasks). In the no control lag and high control lag conditions, subjects failed to fly over 77 of the mines providing for only 2191 cases. Thirty of these cases (1.3%) were determined to be outliers (+3.5 SD), and were removed from the response time data. The frequency of outliers across conditions was roughly equivalent.

ERF and WRF turns

The ERF and WRF turns were analyzed together because they were the only tasks to occur while the subjects were controlling the simulation. The WRF localization occurred while the simulation was frozen and the map reconstruction task occurred following a flight.

Flight performance data. An analysis of the flight performance data for only those tasks in which subjects were maintaining adequate altitude control on task initiation (i.e., within 20 ft. of the desired 50 ft. altitude on task initiation) showed only a significant main effect for flight

difficulty in both RMS altitude error and RMS stick velocity, $F(1, 17) = 20.28$, $p<.001$ and $F(1, 17) = 57.49$, $p<.001$, respectively. These data indicate that subjects maintained their altitude more effectively in the no control lag condition and made more stick inputs in the high control lag condition. The lack of any significant interactions among flight difficulty, map display, or task type in the flight performance data suggests that subjects maintained flight control at the expense of the navigation tasks. Consequently, the remainder of this section focuses on the navigation task RT and error data.

Response time data. Figure 2 presents the RT data for the ERF and WRF turns and shows that the ERF turns were made quicker, $F(1, 17) = 25.65$, $p<.001$, responses using the track-up map were fastest, $F(2, 34) = 7.23$, $p=.002$, and RTs generally increased with heading angle, $F(3, 51) = 21.31$, $p<.001$. Furthermore, these main effects were moderated by several interactions.

The overall faster RTs for the track-up map are apparently due to the absence of an increase in RT as a function of heading that was present with the two north-up designs, $F(6, 102) = 7.34$, $p<.001$. The monotonic increase in RT for the north-up designs is presumably the result of a mental rotation of the display to a track-up orientation before a response could be made. As expected, the ERF turns were not affected by heading as much as the WRF turns, $F(3, 51) = 4.63$, $p=.006$.

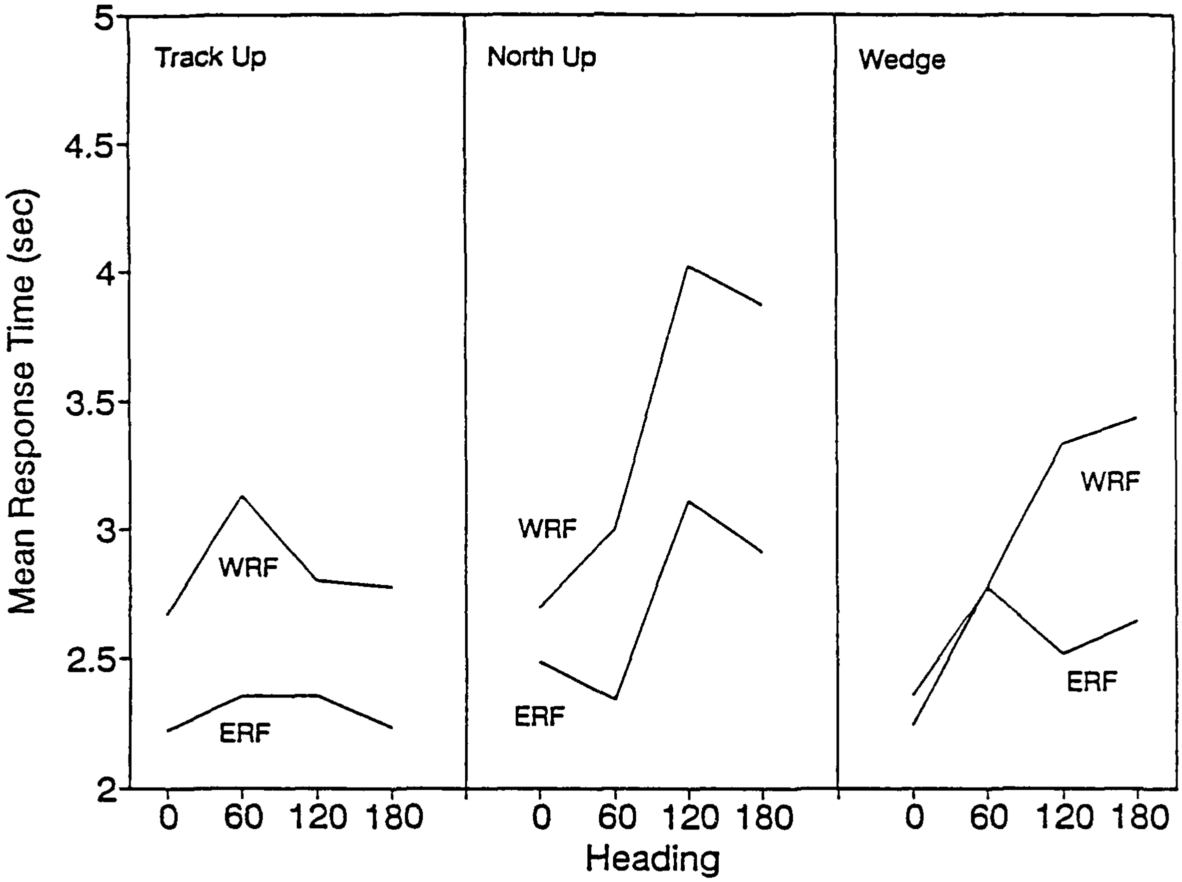

Figure 2. Mean response time as a function of map design, task type, and heading.

This is not surprising since the ERF turns did not require the use of the map. The fact that ERF RTs were somewhat influenced by the north-up designs implies that subjects were using the map on at least some of the trials, $\underline{F}(6, 102) = 4.18$, $\underline{p}=.001$. The suggestion that task type (ERF vs. WRF turns) and map display were differentially influenced by heading was supported by a significant three-way interaction, $\underline{F}(6, 102) = 3.09$, $\underline{p}=.008$. In general, the ERF turns and track-up map were less influenced by heading than the WRF turns and north-up maps.

Another question this research investigated was whether there was resource competition between flight control and navigation. Although there was no main effect in RT for flight difficulty, there were several interactions indicating possible resource competition. The one significant two-way interaction involved flight difficulty and heading, $\underline{F}(6, 102) = 3.44$, $\underline{p}=.004$. Since heading was mainly a factor for the north-up displays and the WRF turns, a separate analysis was performed on these data. Figure 3 shows RT as a function of heading and flight difficulty for the WRF turns collapsed across the two north-up designs, $\underline{F}(6, 102) = 6.13$, $\underline{p}<.001$. The main source of the interaction appears to be the dips in the two flight control functions at 180°.

It was expected that resource competition between flight control and mental rotation might also alter the slopes or intercepts of these functions. Linear regression equations were computed for each condition (i.e., using the first three

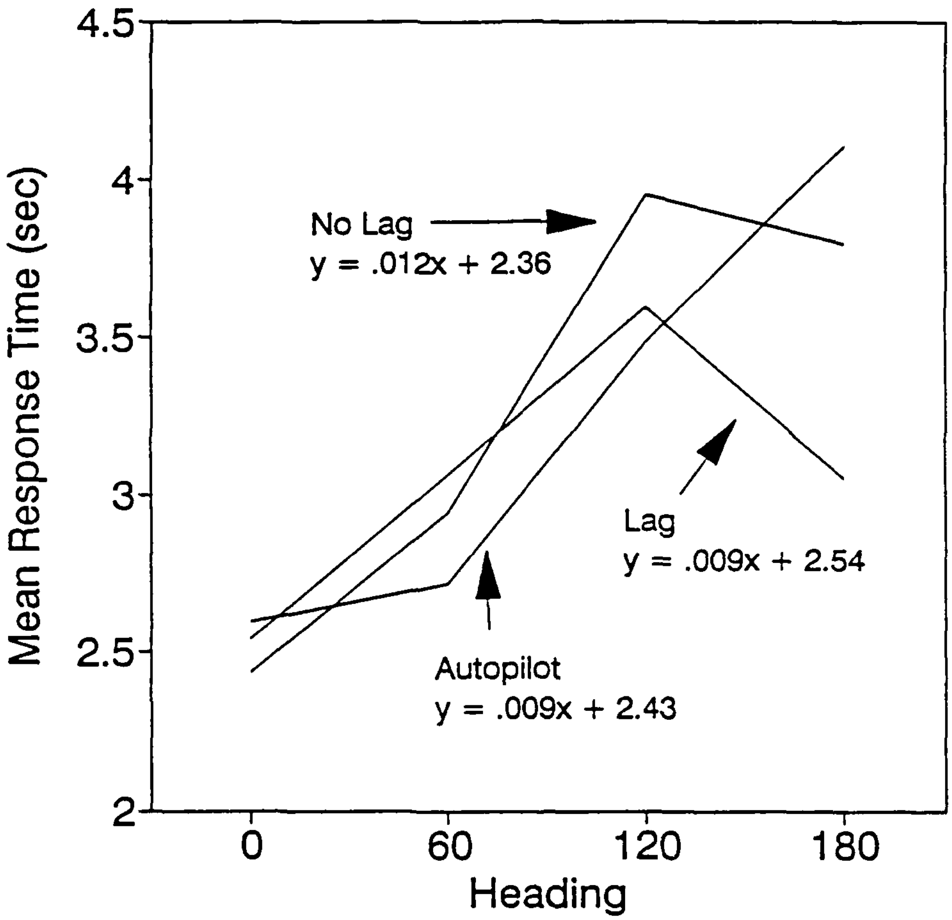

Figure 3. Mean response time as a function of flight difficulty and heading for the WRF turns collapsed across the two north-up displays.

headings in the flight control conditions) and are also presented in Figure 3. An analysis of the first three headings revealed only a significant heading effect, $F(2, 34) = 54.36$, $p<.001$. Hence, the differences among the regression equations are not statistically significant.

The dips in the mental rotation functions at 180° for the two flight control conditions, however, may be indicative of a competition between flight control and navigation. These dips suggest the use of an alternative strategy, other than mental rotation, to perform the task. In this case, a response could be made using the categorical relations associated with the left and right sides of the display. At a 180° heading, the two sides of the map are opposite from their relationship with the forward view and subjects may have used a left=right reversal strategy to perform the task. The dips in Figure 3 suggest that this strategy could be performed more rapidly than a 180° mental rotation.

A finer grained analysis of the WRF turns performed with the two-north up designs provides more detail on the possible use of the reversal strategy. Figure 4 presents a three-way interaction among flight difficulty, map display, and heading, $F(6, 102) = 8.11$, $p<.001$. These plots show that subjects seemed to use the "left=right" strategy for both flight control conditions with the north-up map, but only in the high control lag condition with the wedge display. Figure 4 also suggests intercept differences within the mental rotation functions for

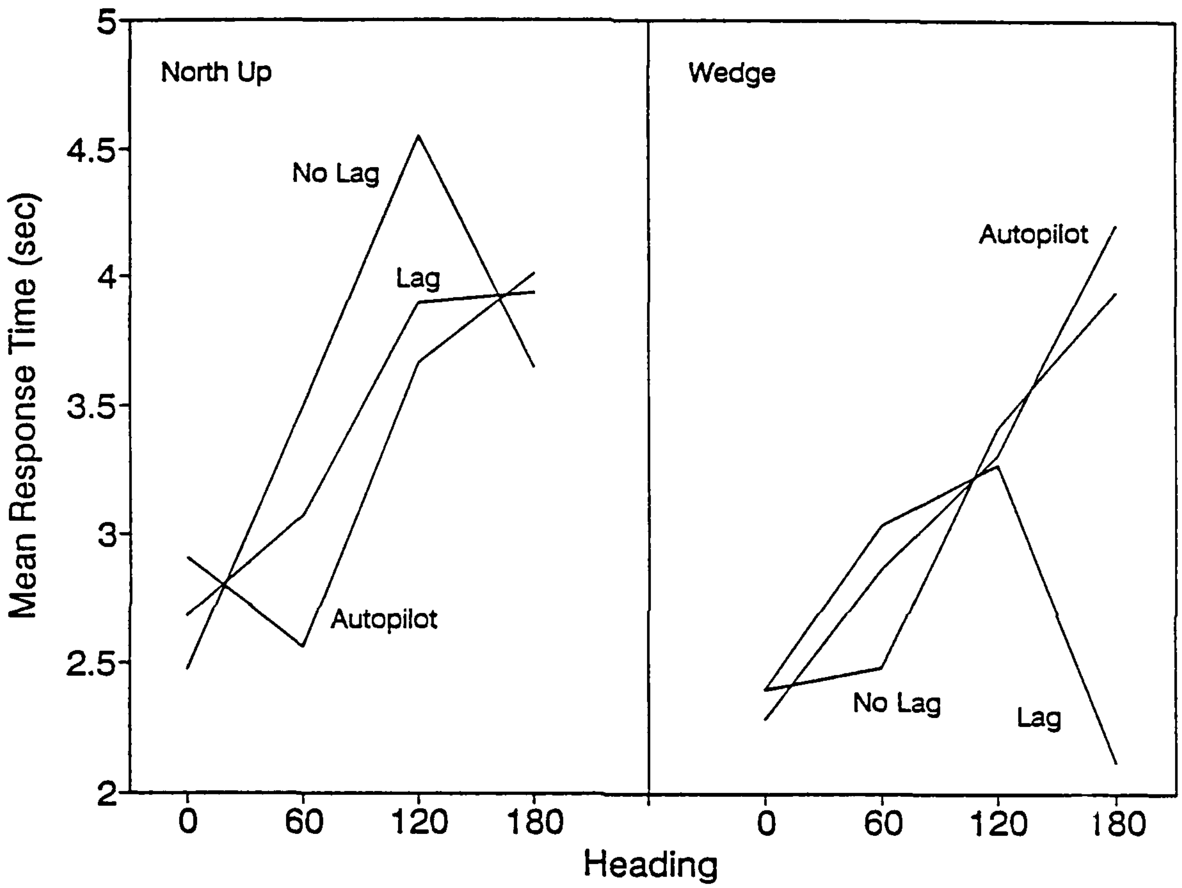

Figure 4. Mean response time for the WRF turns as a function of map display, flight difficulty, and heading.

the north-up design, but not for the wedge design. Figure 4 also shows that the intercepts for the mental rotation functions are generally lower for the wedge display than the north-up display. A regression analysis of the first three headings for the north-up and wedge maps revealed a significant intercept difference of 250 msec between the two displays, $\underline{t}$ = 3.484, $\underline{p}<.001$. These trends indicate that it takes longer to prepare for mental rotation with the north-up display, and that this time may increase with flight difficulty.

Error data. The overall error rates for these tasks were quite low (i.e., 1.6% for the ERF turns and 4.3% for the WRF turns) making it difficult to assess the possibility of speed-accuracy trade-offs in the any of the above effects. Nevertheless, looking at only the WRF turns, there were more errors committed with the north-up display, $\underline{X}^2(2, \underline{N} = 26)$ = 31.0, $\underline{p}<.001$, and in the no control lag condition, $\underline{X}^2(2, \underline{N} = 26)$ = 14.35, $\underline{p}<.001$. There was not a significant interaction, $\underline{p}>.05$ (see Table 1). Fourteen of these errors were the result of one specific treatment involving a WRF turn at a 120° with the north-up map. In looking back at the simulation, if subjects were slightly off a 120° desired heading, the target landmark for this turn may have been close to 180° behind the aircraft. This would have made a left or right turn decision somewhat ambiguous and may have lead to the large number of errors (and an increase in RT for the corresponding points in

Table 1

Number of Errors for the WRF turns

Map Display	Flight Difficulty		
	Autopilot	No Lag	High Lag
Track-Up	0	3	0
North-Up	5	14	3
Wedge	1	0	0

Figures 3 and 4). A separate error analysis without these 14 cases revealed no significant differences among the treatments.

In order to determine if the dips at 180° were due to a possible speed-accuracy trade-off, the errors for heading were also examined. This analysis showed a significant difference among the headings, but again most of the errors occurred as a result of the 120° trial just described, $\underline{X}^2(3, \underline{N} = 26) = 28.46$, $\underline{p}<.001$. The errors for 0, 60, 120, and 180 degrees were 1, 2, 18, and 5, respectively. Without the 14 cases for the 120° case, there was not a significant difference and no appearance of a speed accuracy-trade off.

Variance data. Finally, a regression analysis was performed on the WRF turns and two-north up designs to assess the practical implications of mental rotation. Using the effect sizes as regression variables, the results showed that heading accounted for 17.9% of the variance, followed by the two north-up map designs (3.1%) and flight difficulty (0.8%). These values stand in contrast to 21.5% for differences between the subjects and an error variance of 58%. In order to assess the importance of mental rotation in single (autopilot) and dual task (flight control) conditions, a separate regression analysis revealed that heading accounted for 17.7% of the variance in the autopilot condition and 18.6% in the flight control conditions.

WRF localization

Since the subjects were not flying during the localization task, flight performance data is not discussed. Further, since there were so few cases for the mismatch trials (i.e., they did not occur at all possible headings), these data were analyzed separately from the match trials.

Match trials. The data for the match trials showed that the localization task was performed quickest with the track-up and wedge displays (4.05 and 4.07 sec, respectively, vs. 4.87 sec for the north-up display), $F(2, 34) = 6.50$, $p=.004$, and that RTs increased with heading, $F(3, 51) = 6.79$, $p=.001$. There also was a significant two-way interaction between the map display and aircraft heading, $F(6, 102) = 11.69$, $p<.001$. Figure 5 shows that RT increased with heading for the north-up map, indicating the use of mental rotation during the task. Figure 5 also shows that mental rotation did not seem to be used with the north-up wedge display as might have been expected, but that the function more closely parallels the plot for the track-up map. This result was consistent with the prediction that the perceptual wedge provides visual momentum between the forward view and the map.

As described previously, the number of landmarks visible in the forward view during the comparisons was a nested variable in the experimental design. This manipulation of scene content was grouped into three categories (i.e., one, two, and three or landmarks) for an analysis revealing that RT

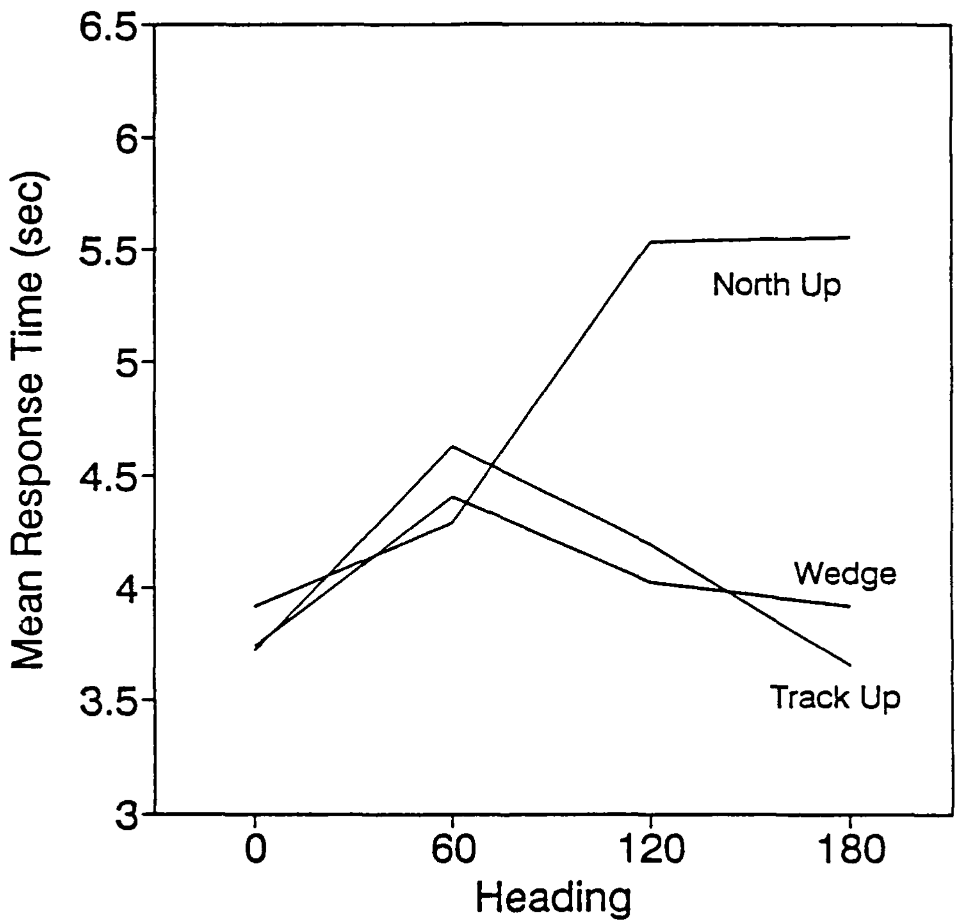

Figure 5. Mean response time as a function of map display and heading for the WRF localization task.

generally increased with scene content, and the scenes with one landmark were localized fastest, $\underline{F}(2, 34) = 24.66$, $\underline{p}<.001$. There was also an interaction between scene content and the map display, $\underline{F}(4, 68) = 4.91$, $\underline{p}=.002$. Figure 6 shows that the RT patterns for the two maps without the perceptual wedge are similar and show little difference between one and two landmarks, but there is a large increase for three or more landmarks. By comparison, the wedge display facilitated performance, relative to the unaided displays, when one or more than three landmarks were in the scene.

Error data. The error data for scene content was also analyzed and showed that there was a significant difference among the three levels of landmarks in the forward view, $\underline{X}^2(2, \underline{N} = 64) = 26.0$, $\underline{p}<.001$, but not among the map displays, $\underline{p}>.05$. However, there was a significant interaction between scene content and map display, $\underline{X}^2(4, \underline{N} = 64) = 26.17$, $\underline{p}<.001$. Table 2 shows that the main source of this interaction is the large number of errors committed with the north-up map in the single landmark condition and with the track-up map in the 3+ condition. It is also important to note that in contrast to the other two designs, the wedge map performed relatively well in all conditions.

Variance data. Finally, a regression analysis was again performed to determine the practical implications of mental rotation. Using the effect sizes as regression variables, the results showed that heading accounted for only 1.0% of the

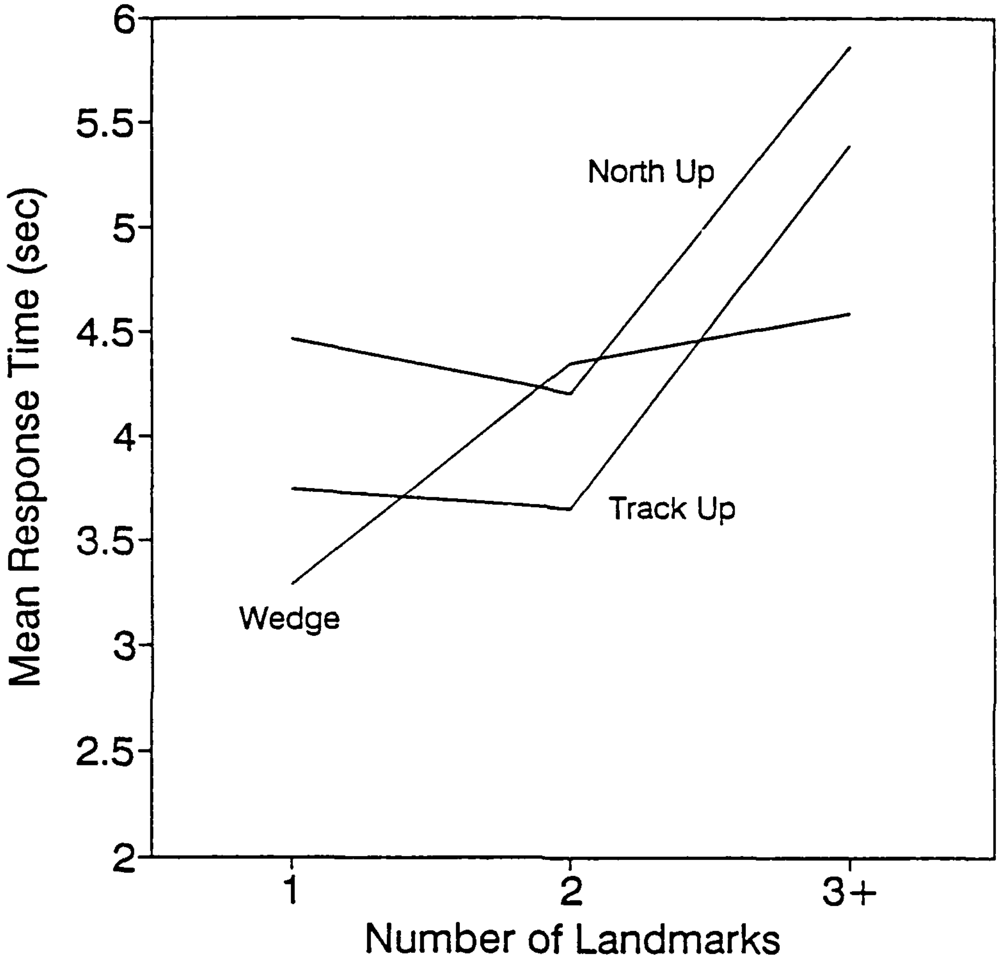

Figure 6. Mean response time as a function of map display and scene content.

Table 2

Number of Errors for the WRF localization task

	Scene Content		
Map Display	1	2	3+
Track-Up	1	3	24
North-Up	13	1	7
Wedge	2	4	9

variance. This is much lower than the 17.9% for the WRF turns, indicating mental rotation did not have as much influence in the localization task. The most powerful variables were scene content and the map display that accounted for 9.4% and 5.5% of the variance, respectively. These values stand in contrast to 30.2% for differences between the subjects and an error variance of 53.8%.

Mismatch trials. The mismatch data revealed that deformations were detected more quickly with the track-up map, $F(2, 34) = 6.49$, $p=.004$. The RT means were 4.08, 5.07, and 4.66 sec for the track-up, north-up, and wedge displays, respectively. Further, there were 33 errors committed with the north-up design, as compared to 13 and 19 with the track-up and wedge displays, respectively, $X^2(2, N = 65) = 9.72$, $p=.008$. Again, the wedge display recovers most of the RT and error costs associated with the standard north-up map.

Task type

One final analysis of the RT data was performed in order to determine the relative difficulty of the three navigation tasks, with mismatch localization data plotted separately, and how they benefited from the different map designs. Figure 7 shows a significant main effect for task type indicating that the turn decisions were easier than the localization task, $F(2, 34) = 67.44$, $p<.001$. Figure 7 also shows that the inclusion of the wedge improved on the performance of the standard north-up map in all the tasks, $F(4, 68) = 3.32$, $p=.015$.

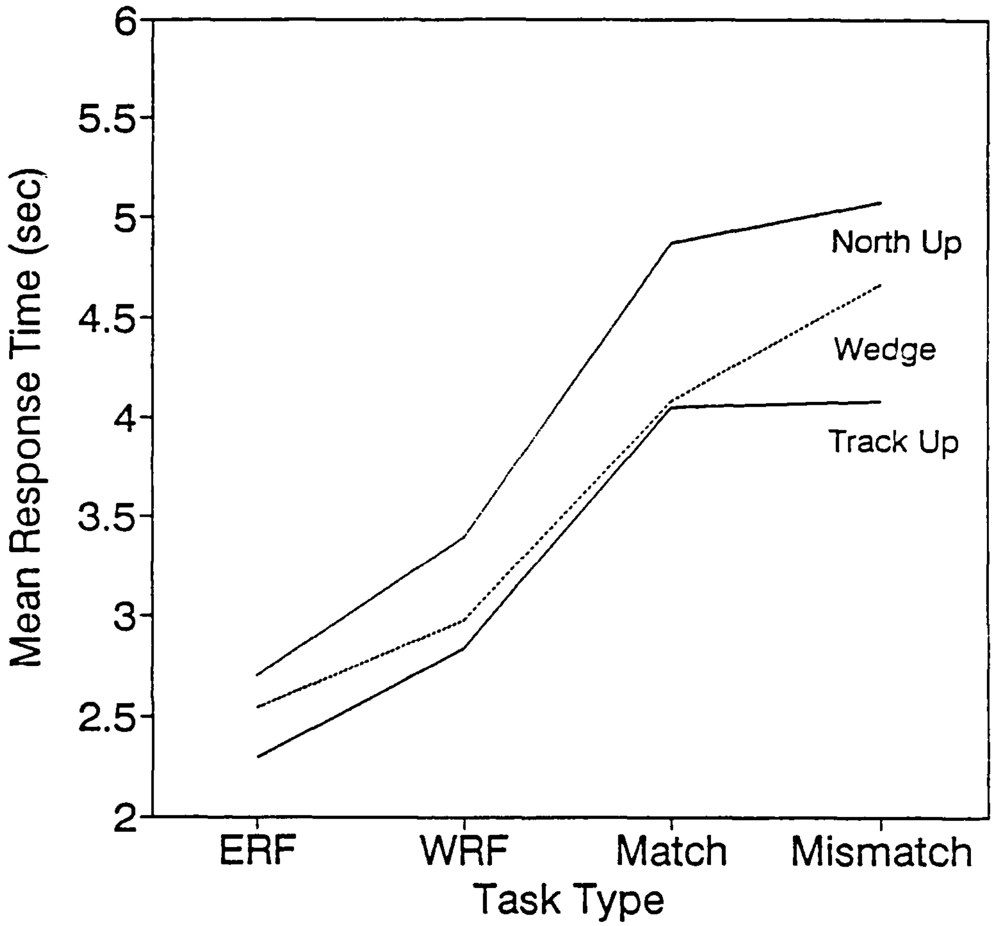

Figure 7. Mean response time as a function of map display and task type.

Map reconstruction

The maps that the subjects sketched on completion of a mission were scored in two ways. The number of landmarks placed in their correct locations were counted, and based on their overall arrangement, a determination was made if the subject had indicated a correct indication for north. The counting of the number of landmarks was somewhat subjective since the maps the subjects drew were not always that accurate. As a result, certain scoring procedures were incorporated to prevent any experimental bias. Specifically, the maps were scored by the experimenter after the completion of the experiment and the scoring was blind as to the treatment. The criteria for scoring was that a landmark was counted as correct if it's location in a relative direction to the other landmarks in the map was correct. For example, if a landmark was to the left and below another landmark, and this was the correct relative location in the true map, then it was counted as correct. If a landmark was placed close to its correct relative location, but not exactly (i.e., within +/- 45°), it was still counted as correct. Further, if there were errors in the map that lead to more than one possible score, the locations of the landmarks leading to the highest score were counted as correct. For example, if there was a group of four landmarks correctly placed relative to each other, but not to another group of three that were also placed correctly relative to each other, the score would be four. Overall, these

procedures probably erred by including extra landmarks, but the same bias was applied to every map.

Since map reconstruction was the only task to rely solely on a WRF, it was expected to benefit from a consistent north-up alignment. As anticipated, Figure 8 shows that more landmarks were recalled in their correct locations with the north-up designs, $\underline{F}(2, 34) = 5.05$, $\underline{p}=.012$. Figure 8 also shows that performance in this task decreased as flight difficulty increased, $\underline{F}(2, 34) = 11.77$, $\underline{p}<.001$. Since there was not a significant interaction between map display and flight difficulty, the scores for each subject were collapsed across flight difficulty and planned comparisons were performed between the track-up map and two north-up designs to see if the north-up alignment facilitated performance. These results showed that there was a significant difference between the track-up map and two north-up maps, $\underline{F}(1, 17) = 17.45$, $\underline{p}<.001$, but not between the two north-up designs themselves, $\underline{F} < 1.0$.

Data was also collected on the number of maps containing a correct indication for north. Although there was a slight increase in the number of times north was indicated correctly with the north-up designs, this increase was not significant.

Subjective ratings

Subjective workload ratings were taken in an attempt to determine if the performance data agreed with the subjects' perceptions of the manipulations. This effort was not entirely successful since the six workload scales only differentiated

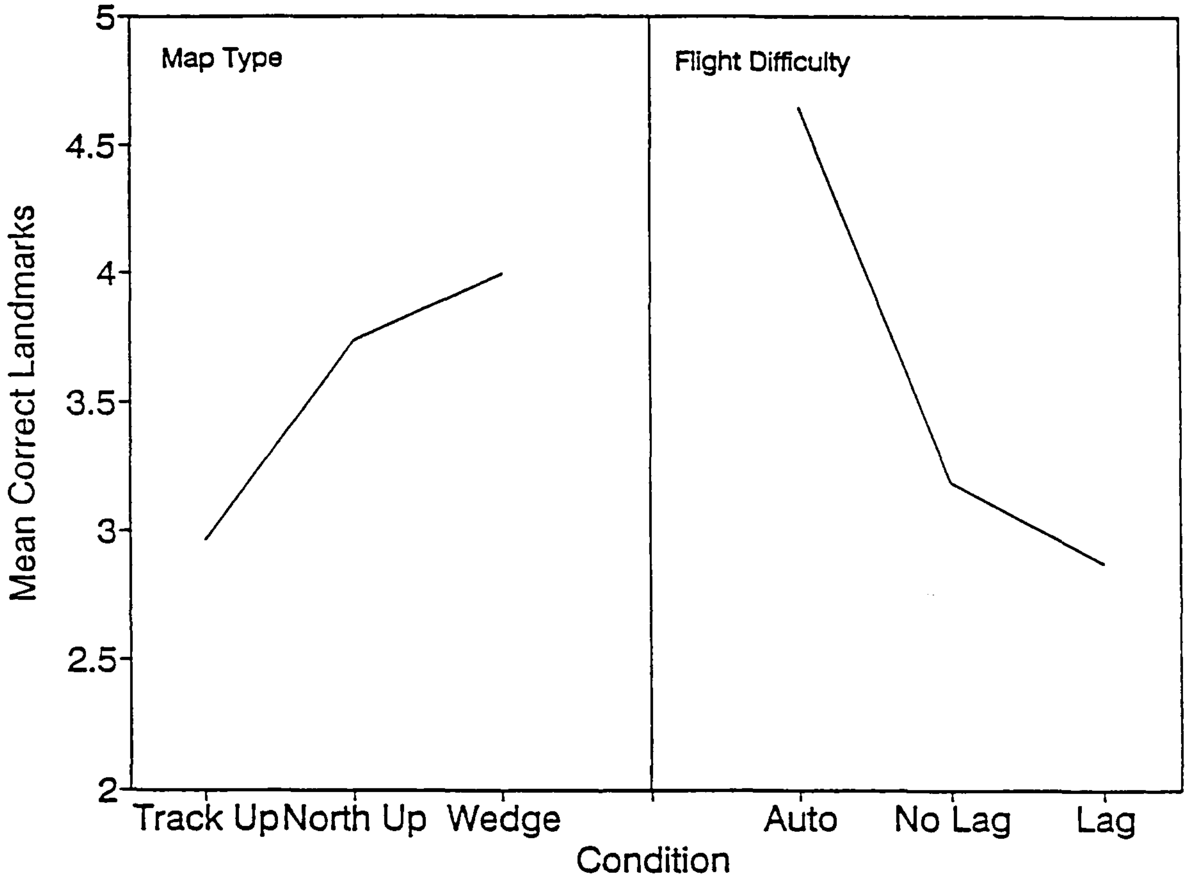

Figure 8. Mean number of landmarks placed in their relative correct location as a function of map display and flight difficulty.

among the three levels of flight difficulty. On a scale from zero to 100, the three levels of flight difficulty received ratings of 25, 38, and 52, for the autopilot, no control lag, and high control lag conditions, respectively, $F(2, 34) = 63.66$, $p<.001$. The were also statistically significant correlations among all six scales. The lowest of these was between perceived performance and physical demands, $r = .83$, $p<.01$.

Questionnaire

The questionnaire given to subjects on their completion of the study contained 20 questions concerning demographics and experimental manipulations. The experimental questions were rated on a seven point Likert scale. Only the most important questions, in relation to face validity and user preferences, will be discussed.

When asked if the experimental tasks were similar or not similar to actual navigation, subjects gave a mean rating of 3.5, which was slightly towards the similar end of the scale. When asked if the experimental tasks were easier or more difficult than actual navigation, subjects gave a mean rating of 3.4, which was slightly towards the easier end of the scale. When asked if they rotate a paper map while navigating, either very often of not very often, subjects gave a mean rating of 3.3, which was slightly towards the very often end of the scale; however, the answers on this question were distributed in a bipolar fashion with 11 of the subjects answering towards

the very often end of the scale. (An additional analysis revealed that this dichotomy was not statically related to performance.) When asked if they used a verbal or spatial strategy in the experiment, subjects gave a mean rating of 5.3, which was close to the spatial strategy end of the scale.

A separate question asked subjects to rank the three map designs according to their preference -- 12 subjects selected the track-up map, one selected the north-up map, and five selected the wedge map. If the wedge map was not selected as the first choice, all subjects picked it as their second choice.

Six of the questions asked the subjects whether the turn decisions or localization tasks were very easy or very difficult for each type of map display, i.e., one question for each task-map display combination. Table 3 shows the ratings for each question.

<u>Psychological testing</u>

The spatial ability tests were given to the subjects in an attempt to discover possible covariates for the prediction of navigation performance. The only significant correlation between the tests and performance in the experiment revealed that subjects with low average solution times in the embedded figures test tended to make no errors in the ERF turn decisions, $r = .69$, $p<.01$. The lack of other significant

Table 3

Mean Questionnaire Ratings for the Two Navigation Tasks and Map Displays (1=Very Easy, 7=Very Difficult)

Map Display	Task: Turn Decisions	Task: Localization
Track-Up	2.10	3.28
North-Up	3.38	3.94
Wedge	2.46	3.06

correlations may be due to a restriction of range effect. Scores on all the tests were much higher than published norms and this elevation was probably the result of licensed pilots serving as subjects. It is logical that someone who is successful at flying, which is a spatial task, would also do well on tests measuring spatial abilities. A restricted range effect was also supported by a lack of significant correlations among the tests themselves. The only significant correlation was between the embedded figures and paper folding tests, $r = .70$, $p<.01$.

Discussion

The data provided by the experiment yielded results that illuminate several of the cognitive operations required for aircraft navigation. The most important feature of the data was the consistency with which it supported the theoretical framework developed earlier. First, the evidence for mental rotation strengthens the suggestion that there are two RFs that must be cognitively aligned to acquire navigational awareness. Second, the changes in the mental rotation functions indicate that navigation competes with the flight control task for the limited spatial processing resources that are available. And third, the effectiveness of the wedge design shows that the principle of visual momentum can be used to facilitate the cognitive coupling between the ERF and WRF. Even on closer examination, the data remain solid in upholding the major tenants of this thesis.

Navigational awareness

The proposed model of navigational awareness includes four cognitive operations -- triangulation, translation, mental rotation, and image comparison. Of these, the experiment only specifically examined triangulation and mental rotation. The four navigation tasks used in the experiment were based on the hypothesis that navigation tasks vary in their requirements for an ERF or WRF, that both RFs must be perceptually triangulated, and that the WRF must be mentally rotated into congruence with the ERF to achieve navigational awareness and perform the task.

In order to test these hypotheses, the four tasks varied on a continuum from one requiring only an ERF (turns to a visible landmark), to two requiring both an ERF and WRF (turns to an occluded landmark and localization), to one requiring only a WRF (map reconstruction). As predicted, these tasks provided data showing differential affects based on their RF requirements.

Triangulation. The localization task included the only manipulation concerning the triangulation component of the model. The data for the two map displays without the perceptual wedge (see Figure 6) depicted roughly the same RT for scenes with one and two landmarks visible in the forward view. If subjects were processing each landmark in the scene, then a serial relationship between scene content and RT would be expected (Aretz, 1988, 1989). The absence of any increase in the two landmark condition indicates that there was a possible facilitation in these trials that counteracted the expected linear increase. Since a unique location is difficult to specify with a single landmark, the second landmark was assumed to decrease the ambiguity in the scene and aided localization. Hence, triangulation performance was aided when two, rather than one, landmarks were visible in the forward field of view. Based on the two-point theorem of spatial problem solving (Levine et al., 1982), this is the minimum amount of information necessary to locate a point on a map. The fact that the task was performed with only a single

landmark indicates that distance to a single point also can be used. Levine et al., generalize both methods by stating that each provides the minimal of two items of information for localization. In either case, the facilitation in the two landmark condition supports the inclusion of a triangulation component in the model of navigational awareness.

The data also showed that the localization task was aided by the ERF perceptual wedge. Figure 6 showed that this effect was especially pronounced in the single and 3+ landmark conditions. Given the two-point theorem of spatial problem solving (Levine et al., 1982), the perceptual wedge probably aided in the single landmark condition by giving a direct indication of triangulation. Further, since only the landmarks inside the wedge of the map needed to be examined, the slope of the complexity effect is less for the wedge display in the 2 and 3+ conditions.

Mental rotation. The model also incorporated the assumption that a north-up WRF would have to be mentally rotated to a track-up alignment (i.e., for headings other than 0°) before a response could be made for a task requiring the cognitive mapping between an ERF and WRF. Two tasks, WRF turns (i.e., turns to an occluded landmark) and WRF localizations, were designed to test this hypothesis. As expected, the RT data from both tasks generally increased with a change in the aircraft's heading away from north, indicating that mental rotation was being used during the task.

Based on previous mental rotation research (e.g., Shepard and Metzler, 1971; Cooper, 1976), this suggestion might only seem warranted if the functions were linear. The differences between the current data and prior research are probably due to differences between the strategies available to the subjects in making comparisons between the stimuli. In most of the past mental rotation experiments, the task could only be performed using mental rotation, resulting in linear functions. Even the experiment on which this task was based found a linear relationship (Shepard and Hurwitz, 1984). Indeed, when mental rotation is being performed on every trial, a linear mental rotation function should be expected. The absence of linearity in the present experiment indicates that mental rotation was not being used on every trial. Therefore, the task may have been performed using alternative strategies.

The main source of non-linearity in the current data was the large decrease in RT at 180° for the two north-up displays. Further, there were no increases in the number of errors that would suggest this decrease was due to a speed-accuracy trade-off. As previously suggested, instead of mentally rotating the map 180°, the subjects may have been using a left=right reversal strategy. Since the data are based on average performance, they presumably represent a mixture of the left=right reversal and mental rotational strategies. Strategies based on other categorical relations (Kosslyn, 1987) also may have been possible at other headings, but were not apparent in the data.

If a left=right reversal strategy is available when a map is presented 180° away from a track-up alignment, it is interesting that Shepard and Hurwitz (1984) did not find anything other than a linear mental rotation function. This result is even more surprising given that the reversal strategy seems to improve performance at 180°. Why did subjects consistently use mental rotation in the Shepard and Hurwitz experiment, but not in the present study? A possible answer is suggested by the plots in Figure 3. Notice that there was a linear mental rotation function for the autopilot (single task) condition, but not the two flight control conditions (dual task). The difference between the two experiments must be based on the dual task nature of the flight control conditions. Since mental rotation is the only strategy available for 60° and 120°, subjects may retain a mental set and not consider switching to the reversal strategy at 180° in the single task condition. When a concurrent task must also be performed, the competition between the tasks may make mental rotation more difficult to perform and make a strategy switch more likely. Since Shepard and Hurwitz only had subjects perform under single task conditions, there was no competition and hence, no evidence for alternative strategies.

Another important result concerning mental rotation was the large increase in the amount of variance explained by the heading manipulation in the WRF turns over the WRF localization task. The rather low percentage of the variance accounted for

by mental rotation in the localization task (1%) is within the same range as the data reported by Aretz for the two mental rotation experiments previously described (1988, 1989). In the 1988 study, mental rotation accounted for three percent of the variance, and in the 1989 study it accounted for four percent.

The large decrease in the variance accounted for in the localization task is likely the result of the influence of the more powerful scene content manipulation that accounted for 9.4% of the variance. (Aretz found that scene content accounted for 12% of the variance in the 1988 data, and 7% in 1989's.) In order to make a response in the localization task, subjects had to first mentally rotate the display and then compare the locations of each landmark in the forward view with its corresponding location in the map. In the WRF turns, on the other hand, subjects had to mentally rotate the display and locate only a single landmark in the map, and then determine if it was on the left or right side. There was no comparison between the map and the forward view in the WRF turns, and as a result, mental rotation was a more influential variable.

Resource competition

The three levels of tracking difficulty were included in the design to examine the competition between navigation and flight control. To the extent that flight difficulty systematically influenced performance on the navigation tasks, an assessment of the resource competition between flight control and navigation can be made. Since flight control and

navigation were hypothesized to require spatial resources, some form of interference was expected. The lack of any significant interactions between flight diffi .ty and navigation in the flight performance data indicate that this interference manifest itself entirely in the navigatic.al performance data. Apparently, the subjects maintained flight control at the expense of navigation. This strategy is entirely logical since flight control must be the primary task in order to maintain aircraft stability and avoid a crash. Other tasks can only be performed after the pilot establishes control of the aircraft.

The cost of the competition between flight control and navigation was chiefly revealed in the mental rotation functions. The mental rotation functions generally indicate that as flight difficulty increased, there was a shift from mental rotation to an alternative non-rotational strategy when it was available. As discussed in the previous section, the left=right reversal strategy at 180° was the main source of evidence for this shift. The fact that this shift only occurred in the dual task flight control conditions, and not in the single task autopilot condition, further supports the suggestion that the strategy shift was the result of competition between flight control and navigation. Since processing resources in general are limited (Wickens, 1980; 1984), subjects chose to reduce the competition for spatial resources by using an alternative strategy when it was available. Based on Wickens (1980; 1984) multiple resource

model, it is also assumed that the alternative reversal strategy consumes verbal, rather than spatial resources.

Figure 4 also shows an important effect of the map design on the competition between flight control and navigation. For the wedge display, the 180° dip was larger and only occurred in the high control lag condition, and for the standard north-up design the dip occurred for both flight control conditions. Since the heading indicator line in the ERF perceptual wedge provides a strong cue separating the display into left and right regions, it is reasonable to conclude that this cue makes the reversal strategy much easier to perform. As a result, subjects readily adopted the reversal strategy with the wedge display in the high control lag condition when there was more resource competition. This choice lead to the more noticeable dip in the wedge display's data. On the other hand, in the standard north-up design, this cue is not explicit and must be inferred by the subject. The absence of large dips in the north-up design suggests that the reversal strategy is not used as often and only when there is resource competition.

The resource competition was also expected to influence the mental rotation function itself. Corballis (1986) found that mental rotation requires attention for it's preparation, but not for it's performance. His data showed that secondary tasks increased the intercept of the mental rotation function from single task conditions, but not the slope. The current experiment basically confirms this hypothesis. Referring back

to Figure 3, there appeared to be no differences in the slope among the mental rotation functions for the different flight difficulty conditions. However, Figure 4 showed that there were increases in the intercepts for the dual task conditions with the north-up map, but not with the wedge map. The wedge may eliminate the intercept differences by reducing the ambiguity of the amount of mental rotation required. The heading line in the wedge map may reduce the preparation time by providing a direct indication of the angular disparity from a track-up alignment. Thus, the current experiment agrees with Corballis in finding increases in the intercepts for mental rotation under dual task conditions, but that these differences may be eliminated by the availability of the proper visual cues.

Figure 8 shows that the map reconstruction data also support the existence of a competition between navigation and flight control in that more landmarks were placed in their correct locations in the autopilot condition than in the flight control conditions. This result suggests that it may be difficult to develop survey knowledge when flight control demands are high due to a scarcity of processing resources.

Map display design

The data were consistent with the cognitive model presented in this thesis in revealing that navigation tasks involving a cognitive coupling between an ERF and WRF (i.e., the WRF turns and localization) would be performed best with a

track-up map. The facilitation associated with the track-up map in these tasks is the result of the congruence of a track-up alignment with the forward view's ERF. No cognitive transformations are required in using the track-up map in making a left or right response since left and right in the map are congruent with left and right in the ERF. The direct correlation between the locations of landmarks in the map and in the forward view also facilitates the WRF localization task.

The suggestion that a track-up alignment facilitates tasks requiring an ERF based response is consistent with the previous literature. Levine (1982) found that subjects perform better with You-Are-Here maps when the objects in the tops of the maps agree with their locations in the forward view. Sholl (1987) also found better performance in a pointing task when the direction that subjects were facing was congruent with their cognitive representation of the environment.

The only cost for the track-up alignment in the two WRF tasks appears in Table 2 as a large increase in the errors committed for the localization task in the 3+ landmark condition. The reason for this large increase in errors may be due to the additional comparisons afforded by the more complex scene. Without the aid of an absolute reference on which to base the comparison, such as the wedge, subjects may have been more likely to see deformations that were not present and make a mismatch response. With a north-up map, direct comparisons

are not possible and subjects may have been biased towards a match response.

Although the incongruence between the forward view and a north-up map may provide a slight advantage in this situation, the incongruence will introduce costs in other situations. An increase in RT and errors will result from the cognitive operations required to transform the map's mental representation into a track-up alignment for tasks involving an ERF. The current experiment provides data that two strategies are available in making this transformation. First, when the WRF turns and localization tasks were performed with a north-up map, there was strong evidence indicating that subjects mentally rotated the map into a track-up alignment before making a response. The monotonic, and sometimes linear, increases in RT as a function of heading are the main supporting evidence for this hypothesis. And second, the dips at 180° in some of these otherwise monotonic functions suggests that a left=right reversal strategy was also being used, particularly at those times when the high spatial demands of flight control competed for the resources associated with large mental rotations. The important point is that both strategies transform an image into a mental representation that is congruent with the ERF.

When a task does not involve an ERF based response, however, there is no requirement to cognitively transform a north-up map. In fact, the only task involving a WRF based

response in this experiment, map reconstruction, was facilitated by a north-up alignment. The reason is that in a north-up display, the locations of the landmarks remain stable in relation to the orientation of the WRF, making it easier to develop survey knowledge of an environment. With a track-up map, the WRF is always rotating to maintain a track-up alignment. In successive views of the display, landmarks are located in different positions relative to the fixed orientation of the display surface, thereby hindering learning. This suggestion is consistent with Harwood's (1989) results showing that judgments of orientation to a specific landmark were aided by a north-up alignment.

A primary interest concerning the map displays was whether the visual momentum provided by the ERF perceptual wedge provided a good design compromise between the traditional ERF compatible track-up, and WRF compatible north-up designs. It was hypothesized that by displaying the ERF wedge in the context of a north-up map, the visual momentum would provide for a more effective cognitive interface in the navigation tasks. In general, the ERF wedge was very effective in recovering the costs associated with a north-up map in making an ERF based response and facilitated the one task requiring a WRF based response.

Although the three tasks occurring during the missions benefited most from a track-up alignment, Figure 7 shows that the wedge display recovers a considerable amount of the RT

costs associated with the standard north-up map. In addition, Table 2 shows that errors were also minimized with the wedge design. The reasons for the improvements in the tasks with the inclusion of the wedge in the standard north-up design can be revealed by examining each task in more detail.

The major cost associated with the standard north-up design was the need for mental rotation. Figure 5 showed that the need for mental rotation in the localization task was practically eliminated by the wedge display. The correspondence between the contents of the wedge and the forward view in a match trial negated the need to mentally rotate the display in the localization task. Although mental rotation was required with the wedge display in the WRF turns, Figure 4 suggests that the improvement with the wedge display in this task was the result of the elimination of the intercept differences among the mental rotation functions for the three flight difficulty conditions. Since there seemed to be intercept differences for the standard north-up design, mental rotation preparation time may have been reduced by the wedge's direct indication of the amount of mental rotation required.

Figure 4 also supports the suggestion that mental rotation is easier with the wedge display by the absence of the reversal strategy for the wedge design in the easy dual task condition (no control lag). Mental rotation could be performed under conditions of higher flight demands with the wedge than with the standard north-up display. When the flight control demands

increased in the high control lag condition, however, the wedge display allowed for the more efficient use of a left=right reversal strategy.

The rather large dip at 180° in Figure 4 for the high control lag condition also indicates that the left=right reversal strategy was made more efficient by the wedge design. This was likely the result of the wedge's heading line that bisected the map into left and right regions.

The data also indicate that the perceptual wedge benefited triangulation, especially when there was only a single landmark in the visual scene. The perceptual wedge aided in the single landmark condition by providing a direct indication of triangulation by the intersection of the two boundary lines of the wedge. As a result, the wedge provided additional cues for triangulation that were not present in the other two displays. With more than two landmarks, the increase in RT with scene content (i.e., the complexity effect) for the wedge display is greatly reduced relative to the other two maps. This effect presumably is due to a decrease in the visual search time for landmarks as a result of the visual cues provided by the wedge. The mismatch data also showed the advantage of the wedge's visual cues in reducing the rather large increase in RT for the standard north-up map. This suggests that the wedge makes inaccurate locations specified on the map more noticeable.

Based on the advantages of the wedge map described above, it can be concluded that this design was effective in

facilitating navigation by providing visual momentum (Woods, 1984). Across all the tasks, the wedge design succeeds in minimizing the costs of a north-up alignment, while retaining its advantages. In this light, it was puzzling that more subjects indicated that they preferred the track-up map in the questionnaire. The reason for this preference may be a function of a bias towards the WRF turn and localization tasks that occurred during the missions when resource competition was present. Although the decisions in this experiment were separated by approximately 10 to 30 sec, situations where the decisions occur more quickly may be further aided by a track-up alignment. For example, performance can be expected to be facilitated by a track-up alignment in high workload NOE flight where turn decisions need to be made quickly and continuously.

The questionnaire also revealed that if the wedge design was not selected as the first choice by a subject, it was always selected as the second choice. There was also a dissociation between the performance and subjective data in the WRF localization task. Although this task was performed faster with the track-up map, the subjects indicated that they preferred the wedge display. On the whole, both the subjective and performance data indicate that the wedge design is an effective compromise between the track-up and north-up designs.

One final comment concerning the wedge display needs to be addressed. For this thesis, the size of the wedge was constrained by the size of the forward view presented by the

computer simulation, i.e., approximately 55°. In the application of this design to actual aircraft, this size might not be optimal. Further, a wedge the size of the normal visual field (approximately 180°) may be too large to provide the benefits of visual momentum. A possible suggestion might be to use reference points created by visual landmarks inside the cockpit, such as canopy support structures, to form the basis of the wedge. In any effect, the optimal size of the wedge still needs to be empirically determined.

Conclusions

The results of this experiment provide evidence for two components, i.e., triangulation and mental rotation, of the cognitive model of aircraft navigation. The two remaining components, i.e., translation and image comparison, remain to be validated. Together, these four components operate to maintain navigation awareness by providing a cognitive coupling between the perceptual view of the world (i.e., the ERF) and a map display (i.e., the WRF).

The data also show that no matter how effective the interface, resource competition between flight control and navigation can be expected. At the same time, this competition can be minimized through the design of an effective display. Based on the results of this thesis, a cockpit navigation display should be designed with the intent to provide an effective cognitive interface for navigation. This was accomplished in the present experiment by providing visual momentum through the presentation of an ERF perceptual wedge in the context of a north-up WRF map display. Normally this coupling must be done cognitively by a pilot, but the wedge provides a perceptual anchor that can be used to allow for more efficient performance. Thus, the optimal design for a navigation display over all tasks would be a north-up map with an ERF perceptual wedge.

However, there still may be situations where a track-up design would be more desireable. If navigation is highly

weighted towards the ERF in a particular application, as in a NOE flight, the congruence between the ERF and track-up alignment would facilitate performance. It is encouraging that the research presented in this thesis provides a theoretical framework by which to make this recommendation.

References

Anderson, J. A. (1978). Arguments concerning representations for mental imagery. Psychological Review, 85, 249-277.

Aretz, A. J. (1988). A model of electronic map interpretation. Proceedings of the 32nd Annual Meeting of the Human Factors Society (pp. 130-135). Santa Monica, CA: Human Factors Society.

Aretz, A. J. (1989). Spatial cognition and navigation. Proceedings of the 33rd Annual Meeting of the Human Factors Society. Santa Monica, CA: Human Factors Society.

Aretz, A. J. & Wickens, C. D. (In Preparation). The mental rotation of map displays.

Baddeley, A. D. & Leiberman, K. (1980). Spatial working memory. In R. Nickerson (Ed.), Attention and Performance VII. Hillsdale, NJ: Erlbaum.

Baty, D. L. (1976). Evaluating a CRT map predictor for airborne use. IEEE Transactions on Systems, Man, & Cybernetics, SMC-6, 209-215.

Baty, D. L., Wempe, T. E., & Huff, E. M. (1974). A study of map display and orientation. IEEE Transactions on Systems, Man, & Cybernetics, SMC-4, 560-568.

Benton, A. L. (1977). Reflections on the Gerstmann syndrome. Brain and Language, 4, 45-62

Benton, A. L. (1982). Spatial thinking in neurological patients: Historical aspects. In M. Potegal (Ed.), Spatial Abilities. New York: Academic Press.

Byrne, R. W. (1982). Geographical knowledge and orientation. In A. W. Ellis (Ed.), Normality and Pathology in Cognitive Functions. New York: Academic Press.

Chase, W. G. (1988). Visual information processing. In K. R. Boff, L. Kaufman, and J. P. Thomas (Eds.), Handbook of Perception and Human Performance, Volume II. New York: Wiley.

Consulting Psychologists Press. (1971). Embedded Figures Test. Palo Alto, CA: Author.

Cooper, L. A. (1976). Demonstration of a mental analog of an external rotation. Perception and Psychophysics. 19(4), 296-302.

Cooper, L. A. & Podgorny, P. (1976). Mental transformations and visual comparison processes: Effects of complexity and similarity. Journal of Experimental Psychology: Human Perception and Performance. 2(4), 503-514.

Cooper, L. A. (1989). Manipulation of visual information. In J. I. Elkind, S. K. Card, J. Hochberg, & B. M. Huey (Eds.), Human Performance Models for Computer-Aided Engineering. Washington, DC: National Academy Press.

Corballis, M. C. (1986). Is mental rotation controlled or automatic? Memory and Cognition, 14, 124-128.

Derrick, W. L., McCloy, T. M., Marshak, W. P., Seiler, G. L., & Reddick, P. A. (1986). The effect of spatial ability on the demand for spatial processing resources. Proceedings of the 30th Annual Meeting of the Human Factors Society (pp. 624-627). Santa Monica, CA: The Human Factors Society.

Derrick, W. L. (1988). Dimensions of operator workload. Human Factors, 30, 95-110.

Ekstrom, R. B., French, J. W., & Harman, H. H. (1976). Manual for Kit of Factor Referenced Cognitive Tests. Princeton, NJ: Educational Testing Service.

Eley, M. G. (1988). Determining the shapes of landsurfaces from topographic maps. Ergonomics, 31, 355-376.

Evans, G. W. (1980). Environmental cognition. Psychological Bulletin, 88, 259-287.

Evans, G. W. & Pezdek, K. (1980). Cognitive mapping: Knowledge of real-world distance and location information. Journal of Experimental Psychology: Human Learning and Memory. 6(1), 13-24.

Friedman A. & Polson, M. C. (1981). Hemispheres as independent resource systems: Limited-capacity processing and cerebral specialization. Journal of Experimental Psychology: Human Perception and Performance, 7(5), 1031-1058.

Geottl, B. (1985). The interfering effects of processing code on visual memory. Proceedings of the 29th Annual Meeting

of the Human Factors Society (pp. 66-70). Santa Monica, CA: The Human Factors Society.

Hart, S. G. & Loomis, L. L. (1980). Evaluation of potential format and content of a cockpit display of traffic information. Human Factors, 22, 591-604.

Hart, S. G. & Wempe, T. E. (1979). Cockpit display of traffic information: Airline pilots' opinion about content, symbology, and format. Moffett Field, CA: NASA Ames Research Center.

Harwood, K. (1989). Cognitive perspectives on map displays. Proceedings of the 33rd Annual Meeting of the Human Factors Society. Santa Monica, CA: Human Factors Society.

Hintzman, D. L., O'Dell, C. S., & Arndt, D. R. (1981). Orientation in cognitive maps. Cognitive Psychology, 13, 149-206.

Hochberg, J. & Gellman, L. (1977). The effect of landmark features on mental rotation times. Memory and Cognition. 5(1), 23-26.

Ishihara, S. (1989). Ishihara's Tests for Colour Blindness. Tokyo, Japan: Kanehara & Co., Ltd.

Kosslyn, S. M. (1987). Seeing and imaging in the cerebral hemispheres: A computational approach. Psychological Review, 94, 148-175.

Levine, M. (1982). YOU-ARE-HERE maps: Psychological considerations. Environment and Behavior, 14, 221-237.

Levine, M., Jankovic, I. N., & Palij, M. (1982). Principles of spatial problem solving. Journal of Experimental Psychology: General, 111, 157-175.

Levy, J., Heller, W., Banich, M. T., and Burton, L. A. (1983). Asymmetry of perception in free viewing of chimeric faces. Brain and Cognition, 2, 404-419.

Liu, Y. & Wickens, C. D. (1987). The effect of processing code, response modality, and task difficulty on dual task performance and subjective workload in a manual system. Proceedings of the 31st Annual Meeting of the Human Factors Society (pp. 847-851). Santa Monica, CA: The Human Factors Society.

Logie, R. H. (1986). Visuo-spatial processing in working memory. The Quarterly Journal of Experimental Psychology, 38, 229-247.

Miller, G. A. (1956). The magic number seven, plus or minus two. Psychological Review, 63, 81-97.

Navon, D., & Gopher, D. (1979). On the economy of the human-processing system. Psychological Review, 86(3), 214-255.

O'Keefe, J. & Nadel, L. (1978). The Hippocampus as a Cognitive Map. Oxford: Clarendon Press.

Pylyshyn, Z. W. (1979). The rate of "mental rotation" of images: A test of a holistic analogue hypothesis. Memory and Cognition, 7, 19-28.

Ratcliff, G. (1982). Disturbances of spatial orientation associated with cerebral lesions. In M. Potegal (Ed.), Spatial Abilities. New York: Academic Press.

Rock, I. & Nijhawan, R. (1989). Regression to egocentrically determined description of form under conditions of inattention. Journal of Experimental Psychology: Human Perception and Performance, 15, 259-272.

Shepard, R. N. and Cooper, L. A. (1982). Mental Images and Their Transformations. Cambridge, MA: The MIT Press.

Shepard, R. N., & Hurwitz, S. (1984). Upward direction, mental rotation, and discrimination of left and right turns in maps. Cognition, 18, 161-194.

Shepard, R. N. & Metzler, J. (1971). Mental rotation of three-dimensional objects. Science, 171, 701-703.

Sholl, M. J. (1987). Cognitive maps as orienting schema. Journal of Experimental Psychology: Learning, Memory, and Cognition, 13, 615-628.

Thorndyke, P. W. & Goldin, S. E. (1983). Spatial learning and reasoning skill. In H. L. Pick & L. P. Acredolo (Eds.), Spatial Orientation: Theory, Research, and Application. New York: Plenum Press.

Thorndyke, P., & Hayes-Roth, B. (1982). Differences in spatial knowledge acquired from maps and navigation. Cognitive Psychology, 14, 560-581.

Wickens, C. D. (1980). The structure of attentional resources. In R. Nickerson (Ed.), Attention and Performance VIII. Hillsdale, NJ: Erlbaum.

Wickens, C. D., Kramer, A., Vanasse, L., & Donchin, E. (1983). The performance of concurrent tasks: A psychophysiological analysis of the reciprocity of information processing resources. Science, 221, 1080-1082.

Wickens, C. D., Sandry, D. L., & Vidulich, M. (1983). Compatibility and resource competition between modalities of input, central processing, and output. Human Factors, 25(2), 227-248.

Wickens, C. D. (1984). Engineering Psychology and Human Performance. Columbus, OH: Merrill Publishing.

Wickens, C. D., Stokes, A., Barnett, B., & Hyman, F. (1988). The effects of stress on pilot judgment in a MIDIS simulator. Armstrong Aerospace Medical Research Technical Report, AAMRL-TR-88-057. Wright-Patterson Air Force Base, OH.

Wickens, C. D. & Liu, Y. (1988). Codes and modalities in multiple resources: A success and a qualification. Human Factors, 30(5), 599-616.

Wickens, C. D., Aretz, A., and Harwood, K. (1989). Frame of reference for electronic maps: The relevance of spatial cognition, mental rotation, and componential analysis. Proceedings of the Fifth International Symposium on

Aviation Psychology. Columbus, OH: Ohio State University.

Wetherell, A. (1979). Short-term memory for verbal and graphic route information. Proceedings of the 23rd Annual Meeting of the Human Factors Society (pp. 464-468). Santa Monica, CA: The Human Factors Society.

Woods, D. D. (1984). Visual momentum: a concept to improve the cognitive coupling of person and computer. International Journal of Man-Machine Studies, 21, 229-244.

Yeh, Y. Y. and Wickens, C. D. (1988). Dissociation of performance and subjective measures of workload. Human Factors, 30, 111-120.

Curriculum Vitae

Anthony Joseph Aretz

Personal Data

[redacted]h:

[redacted]

[redacted]

[redacted]

[redacted]

Education

PhD: 1990, University of Illinois, Champaign-Urbana, Illinois, Engineering Psychology.

MA: 1982, Wright State University, Dayton, Ohio, Human Factors Engineering.

BS: 1980, United States Air Force Academy, Human Factors Engineering.

Work Experience

Jul 87 - Present: Doctoral student at the University of Illinois working with Dr. Chris Wickens and Dr. Art Kramer. Research interests concern human information processing and the modelling of human performance with an emphasis on aviation.

Jul 86 - Jul 87: Assistant Professor at the USAF Academy for the Department of Behavioral Sciences and Leadership. Directed and taught introductory and advanced human factors engineering courses. Was principal investigator

for research investigating issues concerning dynamic function allocation in fighter cockpits.

Jul 84 - Jul 86: Instructor at the USAF Academy for the Department of Behavioral Sciences and Leadership. Taught several courses dealing with general psychology and human factors engineering. Was principal investigator for research investigating the interaction between pilots and expert systems.

Feb 82 - Jul 84: Deputy Technical Director, Cockpit Automation Technology Project, Air Force Aeromedical Research Laboratory, WPAFB. Responsible for the technical aspects of this $42 million program which was to develop a new human factors methodology for cockpit design in the USAF.

Jun 80 - Feb 82: Human Factors Engineer, Flight Dynamics Laboratory, Wright Patterson Air Force Base. Involved in several human factors research projects related to advanced fighter cockpit design. The research emphasized the reduction of pilot workload through the use of advanced pictorial graphic displays, multifunction controls, and speech recognition.

Jun 76 - May 80: United States Air Force Academy Cadet. Held the positions of Wing Sergeant Major (top junior cadet) and Group Commander (one of the top six senior positions).

Jun 74 - Jun 76: Assistant Aircraft Mechanic, Aretz Flying Service, Lafayette, IN. Earned a Private Pilot License in 1976.

Teaching Experience

United States Air Force Academy:

Behavioral Sciences 110: Introduction to Psychology.

Behavioral Sciences 332: Research Design and Statistics.

Behavioral Sciences 373: Human Factors Engineering - Concepts and Theory.

Behavioral Sciences 374: Human Factors Engineering - Application and Evaluation (Course Director).

Behavioral Sciences 450: Biopsychology.

Behavioral Sciences 495: Humans and Computers (Course Director). human/computer interfaces.

Behavioral Sciences 499: Senior Independent Research.

University of Southern California:

Safety and Systems Management 531: Man-Machine Factors in Systems Management.

Special Honors and Awards

Outstanding Student Paper Award, Annual Meeting of the Human Factors Society -- 1989.

Outstanding Military Educator, USAF Academy, Department of Behavioral Sciences and Leadership -- 1986.

Company Grade Officer of the Year, USAF Academy, Department of Behavioral Sciences and Leadership -- 1985.

Military Select Side All Star Rugby Team -- 1982.

Outstanding Young Men of America -- 1982.

Distinguished Graduate, United States Air Force Academy -- 1980.

Outstanding Graduate in the Department of Behavioral Sciences and Leadership, United States Air Force Academy -- 1980.

Professional Organizations

Member, Human Factors Society, since 1979.

Student Member, International Society for Ecological Psychology.

Member, Board of Directors, USAF Academy Association of Graduates (1985-1989).

Aircraft Owners and Pilots Association.

Publications

Papers:

Miller, M. and Aretz, A. (1981). Software Considerations in the Design of Pictorial Flight Displays. In Proceedings of the National Aerospace and Electronics Conference (pp. 544-548). Dayton, OH: IEEE.

Aretz, A. J. (1981). Automatic Return of Control Logic. In Proceedings of the 24th Annual Meeting of the Human Factors Society (pp. 254-256). Santa Monica, CA: Human Factors Society.

Aretz, A. J. and Calhoun, G. L. (1982). Computer Generated Pictorial Stores Management Displays for Fighter Aircraft. In Proceedings of the 25th Annual Meeting of the Human Factors Society (pp. 455-459). Santa Monica, CA: Human Factors Society.

Reising, J. M. and Aretz, A. J. (1982). Color Coding in Fighter Cockpits: It Isn't Black and White. In

Proceedings of the Second Annual Conference on Aviation Psychology (pp. 1-7). Columbus, OH: Ohio State University.

Aretz, A. J. (1983). A Comparison of Manual and Vocal Response Modes for the Control of Aircraft Systems, In Proceedings of the 26th Annual Meeting of the Human Factors Society (pp. 97-101). Santa Monica, CA: Human Factors Society.

Morgan, D. R., Furness, T., Aretz, A. J., Cole, D., and Kulwicki, P. V. (1984). Cockpit Automation Technology Concepts. Farnborough, UK: AGARD Publication.

Reising, J. M., Emerson, T. J., and Aretz, A. J. (1984). Computer Generated Formats for Advanced Fighter Cockpits. In Proceedings of the NATO Workshop on Color vs. Monochrome Displays (pp. 31.1-31.9). Farnborough, UK: AGARD Publication.

Aretz, A. J. (1984). Cockpit Automation Technology. In Proceedings of the 27th Annual Meeting of the Human Factors Society (pp. 487-499). Santa Monica, CA: Human Factors Society.

Aretz, A. J., Guardino, A., Porterfield, T., and McClain, J. (1986). Expert System Advice: How Should it be Given? In Proceedings of the 30th Annual Meeting of the Human Factors Society (pp. 652-656). Santa Monica, CA: Human Factors Society.

Aretz, A. J., Hickcox, J. C., Kessler, S. R. (1987). Dynamic Function Allocation in Fighter Cockpits. In Proceedings

of the 31st Annual Meeting of the Human Factors Society (pp. 414-418). Santa Monica, CA: Human Factors Society.

Reising, J. M., and Aretz, A. J. (1987). Color Computer Graphics in Military Cockpits. In Color and the Computer. John Durrett (Ed.). New York, NY: Academic Press.

Aretz, A. J. (1988). A Model of Electronic Map Interpretation. In Proceedings of the 32nd Annual Meeting of the Human Factors Society (pp. 130-135). Santa Monica, CA: Human Factors Society.

Wickens, C. D., Harwood, K., and Aretz, A. (1989). Frame of Reference for Electronic Maps: The Relevance of Spatial Cognition, Mental Rotation, and Componential Task Analysis. In Proceedings of the Eleventh Annual Conference on Aviation Psychology (pp. 1-7). Columbus, OH: Ohio State University.

Aretz, A. J. (1989). Spatial Cognition and Navigation. In Proceedings of the 33rd Annual Meeting of the Human Factors Society (pp. 8-12). Santa Monica, CA: Human Factors Society.

Technical Reports:

Aretz, A. J. (1983). A Comparison of Manual and Vocal Response Modes for the Control of Aircraft Systems. Air Force Wright Aeronautical Laboratories Technical Report AFWAL-TR-83-3005. Wright-Patterson Air Force Base, OH: Flight Dynamics Laboratory.

Aretz, A. J., Reising, J. M., Kopala, C. J., Calhoun, G. L., and Herron, E. L. (1983). Computer Generated Pictorial Stores Management Displays for Fighter Aircraft. Air Force Wright Aeronautical Laboratories Technical Report AFWAL-TR-83-3005. Wright-Patterson Air Force Base, OH: Flight Dynamics Laboratory.

Aretz, A. J., Guardino, A., Porterfield, T., and McClain, J. (1986). Expert System Advice: How Should it be Given? Frank J. Seiler Research Laboratory Technical Report FJSRL-TR-86-0007. USAF Academy, CO: Frank J. Seiler Research Laboratory.

Aretz, A. J., Hickcox, J. C., and Kessler, S. R. (1987). Dynamic Function Allocation in Fighter Cockpits. Frank J. Seiler Research Laboratory Technical Report FJSRL-TR-87-0004. USAF Academy, CO: Frank J. Seiler Research Laboratory.